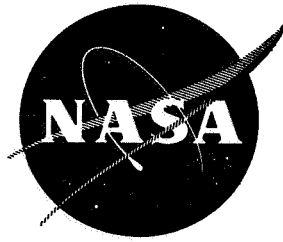


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FINAL REPORT

INVESTIGATION OF THE SUITABILITY OF GELLED METHANE
FOR USE IN A JET ENGINE

by
E. M. Vander Wall

AEROJET LIQUID ROCKET COMPANY
Sacramento, California 95813

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 1971

CONTRACT NAS 3-14305

NASA Lewis Research Center
Cleveland, Ohio

Joseph Ladd, Project Manager

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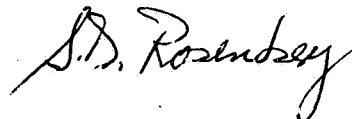
FOREWORD

Contract NAS 3-14305, "Investigation of the Suitability of Gelled Methane for Use in a Jet Engine," was performed by the Aerojet Liquid Rocket Company at Sacramento, California. The performance period was from 15 June 1970 through 15 February 1971.

The Program Manager was Dr. S. D. Rosenberg. The Project Chemist was Dr. E. M. Vander Wall. The experimental work was conducted by Dr. Vander Wall, R. H. Globus, Senior Chemist, J. A. Cabeal, Senior Laboratory Technician, and Dr. R. E. Yates, Chemistry Specialist.

The NASA Project Manager for Contract NAS 3-14305 was J. M. Ladd, NASA-Lewis Research Center.

Approved:

A handwritten signature in cursive script, appearing to read "S. D. Rosenberg".

S. D. Rosenberg, Manager
Propellant Chemical Programs
Engine Components Department

ABSTRACT

The investigation involved (1) evaluation of suitable particulate gelants for liquid methane, (2) characterization of the resulting gels with respect to inhibition of nitrogen absorption, sloshing behavior, venting behavior, and effects of boil-off, and (3) heat exchanger tests to determine potential problem areas in utilizing the gels in jet engines. Both water and methanol were found to be suitable gelants for liquid methane. Liquid methane gelled with water was successfully evaluated in the heat exchanger tests.

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SUMMARY

The objective of this program is the determination of the suitability of gelled methane as a fuel for use in a jet-engine aircraft. The investigation was to determine that (1) increased specific fuel consumption will not be excessive due to the gelant required, (2) the gelled fuel is adequately stable for storage for 100 hr, (3) the use of a gel will not cause the clogging of heat exchangers due to gelant particles, gelant-methane adducts, or decomposition products of the gelant, (4) handling qualities of the gelled fuel are not impaired by anticipated fuel vaporization, and (5) the nitrogen solubilization rate in gelled methane is negligible under various operating conditions.

The program involved three major areas of investigation: (1) selection of gelling agents for liquid methane, (2) characterization of the liquid methane gels, and (3) heat exchanger tests with gelled liquid methane. Small particles of solid water and methanol were found to be very suitable gelants for liquid methane. Characterization of the gels with respect to inhibition of nitrogen absorption, sloshing behavior, venting behavior, and effects of boil-off indicated that less than 1.5 weight percent of water or methanol is adequate to gel the liquid methane. The parameters which govern the quality of gelant particles were identified and the processes for preparation of the gelants were defined.

The heat exchanger tests were conducted with liquid methane gelled with various concentrations of water as gelant. The potential problem areas were defined and the final heat exchanger test was conducted at the design-level flow rate (10 lb/hr, 4.5 kg/hr) for 2 hr without any clogging occurring.

I. INTRODUCTION

The use of liquid methane in jet-engine aircraft promises improved performance over that which can be obtained with conventional liquid hydrocarbon fuels. This is due to the greater capacity of liquid methane as a heat sink and the greater heat of combustion of liquid methane as compared with conventional fuels. However, a potential disadvantage to the use of liquid methane as an aircraft fuel is the "pressure boil-off" problem. Saturated liquid methane at ground level conditions rapidly boils off as the aircraft climbs and the ambient pressure diminishes. This boil-off can be prevented if (1) the tanks are maintained at ground level pressure or (2) the liquid methane is subcooled to a temperature so that the vapor pressure corresponds to saturated conditions at altitude. Subcooling of the liquid methane is the preferred approach.

Liquid methane in the subcooled state can dissolve prohibitive quantities of nitrogen or air. For example, the calculated solubility of nitrogen at a partial pressure of $1 \times 10^5 \text{ N/m}^2$ (one atmosphere) in liquid methane subcooled 13.9°K (25°F) is 11.3 weight percent (Reference 1). Excluding air from the fuel by sealing the tanks containing the subcooled liquid methane results in a vapor pressure less than atmospheric and a load which tends to collapse the tank walls. Pressurizing the ullage space would eliminate the collapsing load on the tanks. Therefore, the practical use of subcooled liquid methane at ground level requires either the use of a nonsoluble pressurant gas or very strong tanks.

Helium, hydrogen, and neon are gases that can be considered as relatively nonsoluble in liquid methane. Each of these pressurants presents a problem. The use of helium and neon presents economic and availability problems, and the use of hydrogen raises questions of safety. If liquid methane can be treated in some manner to reduce its capability to readily dissolve nitrogen so that it can be considered relatively nonsoluble, then the consideration of the use of subcooled liquid methane becomes practical.

One approach to limiting the quantity of nitrogen or air which is dissolved in the liquid methane when used as a pressurant is gelation. Gelation decreases the rate at which gases dissolve in the liquid phase by limiting the mass transfer mechanisms in the liquid phase to a diffusion mechanism. The gelling of liquid methane with water or methanol accomplishes a significant reduction in nitrogen solubility for periods of time greater than ten hours and therefore allows practical consideration of the use of subcooled liquid methane.

The objective of this program is to determine the suitability of using gelled methane as a fuel for a jet engine. The investigation seeks to determine that (1) increased specific fuel consumption will not be excessive due to the gelant required, (2) the gelled fuel is adequately stable for storage for 100 hr, (3) the use of a gel will not cause the clogging of heat exchangers due to gelant particles, gelant-methane adducts, or decomposition products of the gelant, (4) handling qualities of the gelled fuel are not impaired by anticipated fuel vaporization, and (5) the nitrogen solubilization rate in gelled

methane is negligible under various operating conditions. The program consisted of two basic areas of investigation, (1) gelation of liquid methane and (2) heat exchanger tests. The gelants for methane were selected on the basis of being liquids at ambient temperatures, producing no solid residues during combustion, minimum cost, and potential fuel value. The heat exchanger tests were conducted in an apparatus which represented conditions that are encountered in current aircraft heat exchanger systems.

The experimental program was conducted with methane with a minimum purity level of 99.0 mole percent. The gels which were prepared behave as semi-solids when at rest, but "shear-thin" sufficiently when stress is applied that the flow behavior approximates that of the liquid itself. The gels have a consistency at rest approximating that of the commercial "hair-setting" gels.

II. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental investigation is conveniently divided into two major topics: (1) Gelation Investigation, and (2) Heat Exchanger Tests. The results are presented accordingly.

A. GELATION INVESTIGATION

The gelation investigation consisted of the selection of suitable gelants for liquid methane, and the characterization of the gelled liquid methane. The discussion is presented under two headings: (1) Gelant Selection, and (2) Gel Characterization.

1. Gelant Selection

Gels can be classified according to the manner in which they are produced; they are prepared either by using particulate gelling agents or swellable polymers. The particulate gelling agents, though insoluble in the solvent to be gelled, possess sufficient attractive forces at their surfaces to impart a gel structure to the selected liquid. The swellable polymers actually solubilize to some extent in the solvent to be gelled. The degree of gelation in the liquid is dependent on how well the solvent solubilizes the polymer. The polymeric-type gelling agents produce gels which maintain their structural integrity as long as the gel is maintained within a temperature range where the solvent characteristics of the gelled liquid remain adequate for the polymer. Unfortunately, at low temperatures, i.e., 200°K (-100°F), no inexpensive polymeric gelling agents are available for gelling hydrocarbons because of the insolubility of the polymers in hydrocarbons in this temperature regime.

On the other hand, particulate-type gelling agents produce gels in liquids which are nonsolvents for the particles. The gels produced by particulate gelants generally have a tendency to exhibit some degradation of gel structure during extended storage periods. The structural degradation is evidenced by the appearance of some ungelled liquid on the surface of the gel. Generally, the structural integrity of the gel remains adequate for at least a period of weeks. Based on the foregoing, it is apparent that a particulate-type gelant would be quite appropriate for the gelation of liquid methane for applications in which prolonged storage periods are not required.

The basic requirements for the functioning of particulate gelants are: (1) they are sufficiently small to possess a very high surface area per unit mass so that the attractive forces among the particles become appreciable; and (2) the gelant particles are insoluble in the liquid of interest so that particle growth does not occur. Because it is desirable that (1) the gelling agent cost be comparable to that of methane itself from an economic standpoint and (2) the gelling agent does not deposit any solid residue during or after use, the most prominent candidate gelant for methane was very

small particles of solid water. From a solubility consideration, water is an excellent candidate. Water, however, does not possess any fuel value in an air oxidation process. Other gelant candidates included in the investigation were: methanol, ethanol, isopropanol, tertiary butanol, ammonia, and carbon dioxide.

a. Method of Gelant Particle Preparation

The method used for the preparation of small particles of gelants in this investigation was originally developed for the preparation of micron-size particles of solid chlorine trifluoride for gelation of liquid oxygen difluoride (Reference 2). The same technique has been used to prepare small particles of hydrocarbons for the gelation of liquid hydrogen (Reference 3).

The basic method involves the dilution of the candidate gelant vapor with an inert carrier gas, followed by injection of the gaseous mixture through a suitably heated tube and orifice directly into a cryogenic liquid so that condensation occurs immediately within the bulk of the liquid. The direct dispersion of the particles in the liquid avoids the condensation of particles on the walls of the vessel and eliminates the necessity of additional mixing normally required to produce a gel.

For the scoping experiments in which the relative effectiveness of candidate gelants was evaluated, a simple apparatus was used. A 10 cm dia x 35 cm long Pyrex flask fitted with a three-port cover was used as the gelling vessel. One port was used for introduction of methane; the second port was used for the heated tube for introduction of the diluted gelant vapor into the liquid methane; and the third port served as the vent. The gelling flask was immersed in a transparent Dewar to which liquid N_2 was added as refrigerant.

b. Experimental Results

Methanol as Gelant - Methanol vapor diluted with either helium or methane was passed through a heated tube and injected into liquid methane through a 0.063 cm (0.025 in.) dia orifice located several cm below the surface of liquid methane. The majority of the experiments were conducted with 40:1 volume ratio of carrier gas to methanol vapor and the pressure drop across the orifice was $3.6 \times 10^5 \text{ N/m}^2$. The liquid methane was either subcooled to slightly above its melting point or maintained at its normal boiling point during the experiments. Indications of gel structure were determined by measuring the weight of various spheres that could be supported by the gel and by observing the trapping of gas bubbles in the bulk of the liquid. The data are presented in Table I.

TABLE I. - DATA INDICATIVE OF THE EFFECT OF VARIOUS PARAMETERS
IN THE PREPARATION OF SOLID METHANOL PARTICLES
AS A GELANT FOR LIQUID METHANE

Experiment	Carrier Gas	Dilution Ratio, Carrier/CH ₃ OH	Condition of Liquid Methane	Remarks
6a	CH ₄	40/1	Subcooled	At <0.3 wt%, gelant particles settle
6b	He	40/1	Subcooled	At 0.3%, gelant particles do not settle
6c	CH ₄	40/1	Boiling	At <0.3%, gelant particles do not settle
2	CH ₄	40/1	Boiling	Structure index, <80 N/m ² at 8.2%
5	CH ₄	40/1	Subcooled	Structure index, <27 N/m ² at 4.0%
7a	He	40/1	Subcooled	At 4.6%, gelant particles do not settle Structure index, ~27 N/m ² at 4.7% Structure index, >27 N/m ² at 5.6%
7b	CH ₄	40/1	Boiling	At 4.7%, gelant particles do not settle Structure index, <27 N/m ² at 6.0%
8	CH ₄	40/1	Boiling	Structure index, <27 N/m ² at 4.9% Structure index, >27 N/m ² at 6.5%
9	He	40/1	Boiling	Structure index, ~27 N/m ² at 3.3% Structure index, >80 N/m ² at 4.7% Structure index, 270 N/m ² at 5.5%
17	He	200/1	Boiling	~1 mm dia gas bubbles are immobilized at 1.1% gelant Structure index, >80 N/m ² at 2.5%
18	CH ₄	150/1	Boiling	<1 mm dia gas bubbles are immobilized at 1.3% gelant ~1 mm dia gas bubbles are immobilized at 1.9% gelant

Experiments 6a, 6b, and 6c were conducted to determine the effect of the carrier gas and liquid methane condition on the gelant particle size. The settling of the solid methane particles in Experiment 6a and the lack of settling in Experiments 6b and 6c indicate that the methanol particles produced in Experiment 6a are larger and consequently less desirable for gelation. In Experiment 6a, it was observed that the injected gas bubbles collapsed completely in the liquid methane; in Experiments 6b and 6c they did not collapse completely. Based on these observations, it is apparent that if methane is used as the carrier for methanol, the liquid methane should be maintained at its normal boiling point during the particle preparation step.

A comparison of the results from Experiments 2, 5, 7b and 8 with Experiments 7a and 9 indicate that the use of helium as a carrier gas is preferable to the use of methane in the preparation of methanol particles. At comparable concentration levels, greater gel structure is achieved with methanol particles produced using helium as the carrier gas than with methane.

Increasing the dilution ratio of carrier gas to gelant vapor results in the formation of smaller gelant particles. This can be deduced by comparing the data from Experiments 8 and 9 with that from Experiments 17 and 18; e.g., 4.7% methanol is required to produce a gel with a structure index of $>80 \text{ N/m}^2$ in Experiment 9, while only 2.5% methanol is required to produce comparable structure in Experiment 17.

One additional item to be noted from the data in Experiment 17 is that gas bubbles are trapped in the bulk of the gel with 1.1% methanol present; this is indicative that the convective transfer mechanism has been eliminated. To prevent solubilization of nitrogen in liquid methane, the structure index value may be considerably less than 80 N/m^2 .

The "structure index" value is similar to a yield stress value. The "structure index" is measured by gradually lowering weighted spheres onto the surface of the gel. From the known weight of the sphere and observation of the depth to which the sphere sinks into the gel, the force/area which the gel structure can support is calculated and this value is referred to as the structure index.

Water as Gelant - Based on the experimental results obtained with methanol, helium was used initially as the carrier gas for water in the preparation of ice particles to serve as gelants for liquid methane. The experiments were conducted in a manner similar to that used for the preparation of methanol particles. One experiment was conducted with methane as the carrier gas for the water. The data from the experiments are presented in Table II.

TABLE II. - DATA INDICATIVE OF THE EFFECT OF VARIOUS PARAMETERS
IN THE PREPARATION OF SOLID WATER PARTICLES AS
GELANT FOR LIQUID METHANE

Experiment	Carrier Gas	Dilution Ratio, Carrier Gas/H ₂ O	Condition of Liquid Methane	Remarks
13	He	40/1	Boiling	Sufficient structure to immobilize small gas bubbles at 1.8% Structure index, $>27 \text{ N/m}^2$ at 3.1%
14	He	40/1	Boiling	Added 0.4% trimethylamine to the H ₂ O Sufficient structure to immobilize $>1 \text{ mm}$ dia gas bubbles at 1.5% H ₂ O Structure index, $\sim 27 \text{ N/m}^2$ at 2.8% Structure index, 80 N/m^2 at 7.0% Structure index, 270 N/m^2 at 8.7%
15	He	200/1	Boiling	Gas bubbles immobilized at 1.3% Structure index, $>80 \text{ N/m}^2$ at 2.9%
16	CH ₄	200/1	Boiling	Gas bubbles immobilized at 1.0%

The significant items to be noted from the data are that (1) methane is comparable or better than helium as the carrier gas for the water, (2) increasing the dilution ratio of carrier gas to gelant from 40:1 to 200:1 results in more effective gelant particles, i.e., compare Experiment 14 with Experiment 15, and (3) a structure index value less than 27 N/m^2 is sufficient to eliminate a convective transfer mechanism from the liquid methane. The data indicate that significantly less than 2% water should inhibit the solubilization of nitrogen in the liquid methane.

The gels produced in Experiments 15 and 16 were translucent, while the gels produced in Experiments 13 and 14 were opaque. The translucent appearance can be attributed to smaller size gelant particles. The trace of trimethylamine introduced in Experiment 14 was used to determine if, in prior experimental work, traces of trimethylamine may have contributed to the gelation process. A comparison of the data demonstrates that trimethylamine does not affect the gelation significantly.

Carbon Dioxide as Gelant - A gaseous mixture of helium and carbon dioxide was prepared in a ratio of 40:1 and injected into liquid methane at its normal boiling point. The carbon dioxide particles settled rapidly as agitation ceased and the settled volume of carbon dioxide particles in the liquid methane corresponded to greater than 15 weight percent carbon dioxide in the methane. The settled volume exhibited no gel structure. Based on the observations, carbon dioxide is not a suitable gelant for methane.

Ammonia as Gelant - A gaseous mixture of helium and ammonia was prepared in a ratio of 40:1 and injected into liquid methane at its normal boiling point. The ammonia particles gradually settled in the liquid methane, but eventually a gel was formed. At 16.5% ammonia in methane, the gel had a structure index greater than 80 N/m^2 . Because comparable structure can be produced with less than one half the amount of methanol or water, ammonia is less satisfactory for gelation of liquid methane than methanol or water.

Ethanol as Gelant - Ethanol vapor diluted with methane in a ratio of approximately 1:40 was injected through a 0.025 in. (0.063 cm) orifice positioned below the surface of the liquid methane. The particles of ethanol agglomerated and settled from the suspension during the experiment. The behavior is indicative of some solubility of ethanol in liquid methane. Sufficient ethanol was added to correspond to 4.5 weight percent in liquid methane. The formation of large particles of ethanol which agglomerated further on standing demonstrates that ethanol is not a suitable gelant for liquid methane.

Isopropanol as Gelant - Isopropanol vapor diluted with methane in a ratio of approximately 1:40 was injected through a 0.025 in. (0.063 cm) orifice positioned below the surface of the liquid methane. The particles of isopropanol agglomerated and settled from the suspension during the experiment. This behavior is indicative of some solubility of isopropanol in liquid methane. Sufficient isopropanol was added to correspond to 6.8 weight percent in liquid methane. The formation of large particles of isopropanol which agglomerated further on standing demonstrates that isopropanol is not a suitable gelant for liquid methane.

Tertiary Butanol as Gelant - Based on the unfavorable results obtained with ethanol and isopropanol, tertiary butanol was eliminated from further consideration due to its similarity to the unsatisfactory alcohols.

c. Discussion of Results

The data from the scoping experiments indicated that both methanol and water are suitable gelants for liquid methane, and that a gelant concentration of less than 2 weight percent would be adequate. The data also indicated that ethanol, isopropanol, ammonia, and carbon dioxide are unsatisfactory gelants at the concentration levels considered acceptable, i.e., less than 5 weight percent in liquid methane.

In addition, the effect of the carrier gas (methane or helium) in the preparation of gelant particles was evaluated using both water and methanol as the gelants, and the effect of the carrier gas/gelant vapor dilution ratio was evaluated at two concentration levels. The data show that (1) helium is a better carrier gas than methane for the preparation of methanol particles in liquid methane, (2) a high dilution ratio favors the formation of small particles of both methanol and water, and (3) both helium and methane are equally suitable as carrier gases in the preparation of colloidal ice particles for the gelation of liquid methane.

Based on the foregoing results, both water and methanol warranted further investigation as gelants for liquid methane. The resultant gels were characterized.

2. Gel Characterization

The gel characterization is divided into five experimental categories to determine (1) the solubilization rate of gaseous nitrogen in both gelled and ungelled liquid methane, (2) the effect of sloshing on the solubilization rate of gaseous nitrogen, (3) the effect of aging the gel on the solubilization rate of gaseous nitrogen and the sloshing characteristics, (4) the effect of gelation on the venting characteristic of the fuels, and (5) the effect of increased gelant concentration during fuel evaporation on expulsion efficiency and sloshing. The program guidelines were: (1) to define the gelant concentration at which less than 1 weight percent nitrogen dissolved in gelled liquid methane during one hour under static conditions and (2) to define the gelant concentration at which less than 3 weight percent nitrogen dissolved in gelled liquid methane under sloshing conditions for a period of five minutes in the experimental apparatus. Both water and methanol were used as the gelants for liquid methane in the characterization experiments; and the factors affecting the gelant particles during preparation were further evaluated in these experiments.

The results are presented and discussed under four headings for the sake of clarity. The headings are: (1) Solubilization Rate of Gaseous Nitrogen in Liquid Methane Under Static and Sloshing Conditions, (2) Effect of Gel Aging on the Gaseous Nitrogen Solubilization Rate and the Sloshing Characteristics, (3) Effect of Gelation on the Venting Characteristics of the Fuel, and (4) Effect of Gelant Concentration on Expulsion Efficiency and Sloshing. The results are presented in this order.

a. Solubilization Rate of Gaseous Nitrogen in Liquid Methane Under Static and Sloshing Conditions

Apparatus and Procedures - A schematic diagram of the heated tube used to inject the diluted gelant vapor into liquid methane is shown in Figure 1. The gaseous mixture is prepared by passing helium or methane through the liquid gelant to entrain gelant vapor. The liquid gelant

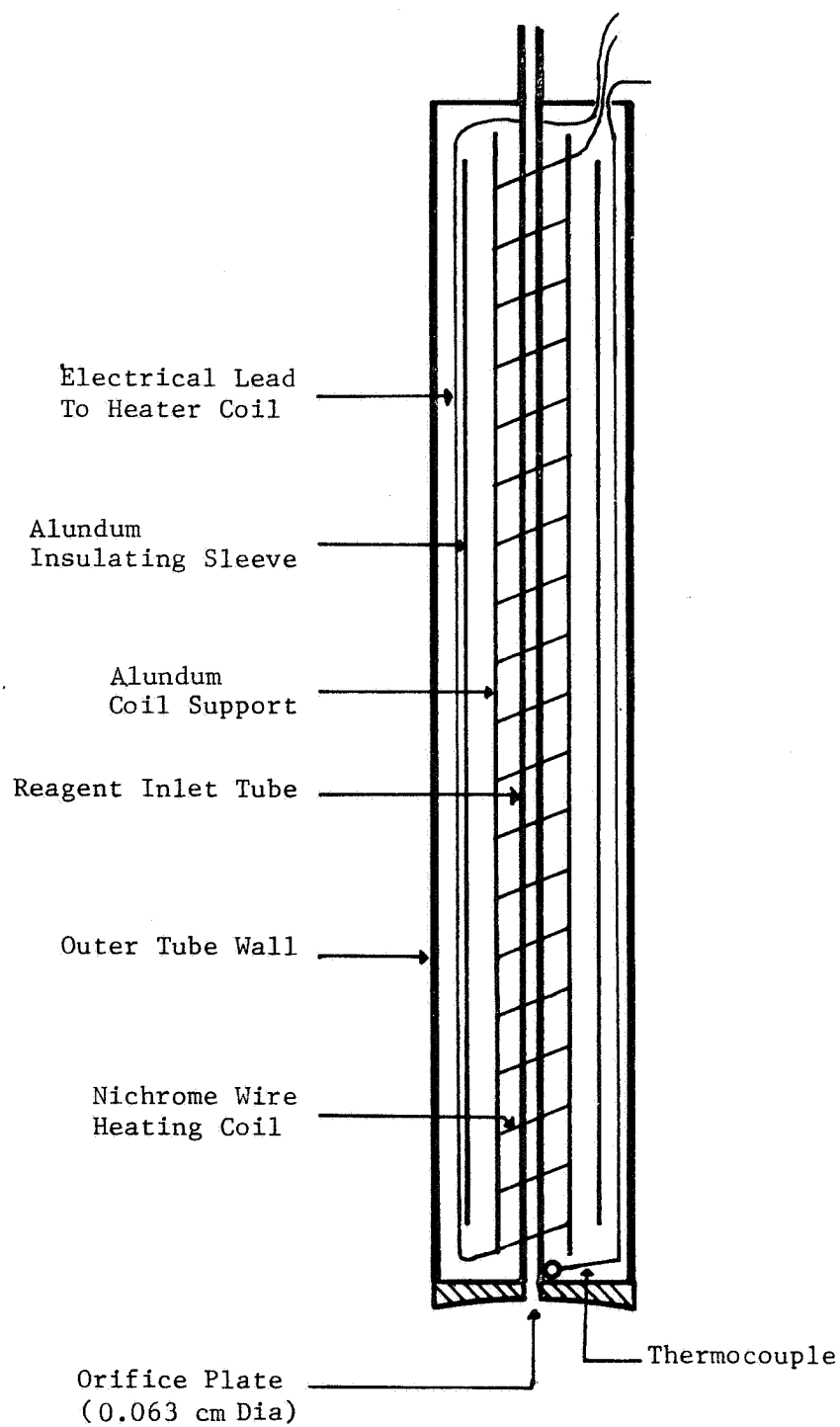


Figure 1. - Schematic of Heated Injection Tube

is contained in a stainless steel bomb which is immersed in a constant-temperature bath. The composition of the gaseous mixture is controlled by the temperature of the liquid gelant and the total pressure in the stainless-steel bomb. The transfer line between the saturation vessel and the injection tube is heated by glass heating tapes to prevent condensation of gelant vapor in the line. The assembled gelling apparatus is shown in Figure 2. The gelling vessel is a 10 cm dia pyrex flask 35 cm long. The top edge has an O-ring groove which is fitted with a Kel-F O-ring to provide a seal between the flask and the aluminum plate cover (0.63 cm thick). The cover is fabricated with provisions for a helium sparge tube, liquid methane inlet, gelant injection tube, and a vent line. The tubing connections are made with AN fittings, and Teflon O-rings are installed as needed. The entire gelling vessel is attached by bulkhead fittings to the cover of a constant-temperature box. The box is fabricated with Plexiglass ports for observation purposes.

The temperature in the box is maintained at $\pm 1.7^\circ\text{K}$ ($\pm 3^\circ\text{F}$) by the periodic addition of liquid nitrogen to the interior of the box.* A helium-gas thermometer provided the detection data required for automatic temperature control. Gaseous methane is prechilled before introduction into the methane condenser coil by passage through a Dry Ice-methanol bath. The liquid methane is added directly to the gelling vessel from the methane condenser coil. During the entire preparative procedure, the apparatus is maintained under a helium atmosphere to prevent contamination of the methane by nitrogen.

After the gels are prepared, they are transferred through a side-arm of the gelling flask to a cylindrical storage flask (4.8 cm ID x 45 cm high) located adjacent to the gelling flask (see Figure 2). The transfer line is equipped with a 1.27 cm Jamesbury ball valve to isolate the flasks. Although this valve is external to the box, provisions are made so that it can be temperature-conditioned before gel transfers. After completion of the gel transfer, the storage flask fill-tube is sealed externally to the box with an AN plug. For sloshing experiments, a rod was suspended from a variable speed cam and attached to the AN plug. By this means the storage flask was oscillated vertically and the contents were sloshed.

The gels were prepared in approximately two liter quantities with subsequent evaporation of methane from the gel to attain the desired concentration of gelant in the methane. A portion of the gelled material was transferred to the storage flask in the constant-temperature bath for measurement of the nitrogen solubilization rate. Under static conditions, the liquid methane was exposed to nitrogen at a partial pressure of $1.013 \times 10^5 \text{ N/m}^2$ (one atmosphere) of nitrogen and the temperature was maintained near 97°K , which corresponds to 14°K (25°F) below the normal boiling point of methane.

*Although the temperature of the box cycled within $\pm 1.7^\circ\text{K}$ ($\pm 3^\circ\text{F}$), the temperature of the liquids in the Pyrex glass vessel does not vary more than $\pm 0.5^\circ\text{K}$ ($\pm 0.9^\circ\text{F}$).

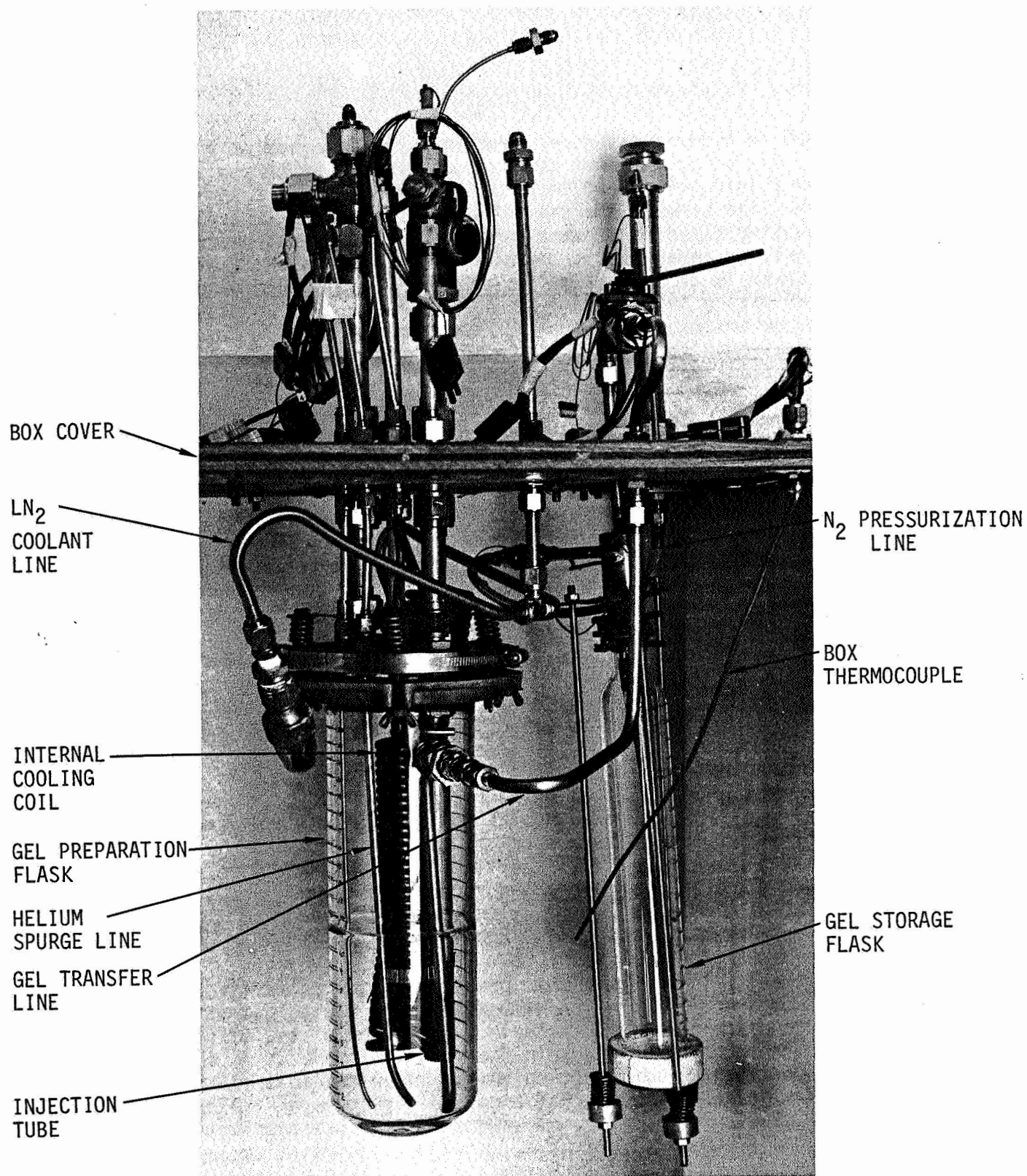


Figure 2. - Assembled Gel Preparation Apparatus

The same storage flask was raised and lowered at a frequency of approximately 80 to 100 cycles/min with an amplitude of 3 cm to produce violent sloshing in the liquid methane while the nitrogen solubilization rate was determined. The cross-sectional area of the storage flask was 18.12 cm².

The quantity of nitrogen dissolved in the liquid methane was measured by two methods, (1) the pressure drop which occurred in a constant volume reservoir, and (2) the change in volume of the liquid as it was exposed to the nitrogen. The pressure measurement method was sensitive to approximately 0.05 gm of nitrogen, and the volumetric method was sensitive to approximately 0.5 gm of nitrogen. The volumetric method was hampered by the inability to detect the liquid-vapor interface distinctly in some instances. The pressure method is satisfactory as long as no leaks occur in the apparatus. No leaks occurred during these experiments. Therefore, the data obtained by the pressure drop method are considered as reliable, conservative values and the data obtained by the volumetric method are considered as a secondary means of confirming the pressure drop data.

Experimental Results with Ungelled Liquid Methane -

Experiments were conducted with ungelled liquid methane to determine the extent to which nitrogen would dissolve in the liquid methane under static conditions for one hour and during five minutes of sloshing. Data from a typical experiment is presented in Figure 3. During these experiments, the temperature of the liquid methane increased initially due to the dissolution of the relatively warm nitrogen. As the liquid approached the saturation point with nitrogen, the temperature of the liquid gradually decreased to the desired value of 97°K (-284°F). The quantity of nitrogen which dissolved under static conditions ranged from 8.1 to 13.8 weight percent, depending to some extent on the quantity of liquid methane initially present in the storage vessel.

The data for a typical experiment in which the liquid methane was sloshed for five minutes is presented in Figure 4. The liquid methane was sloshed at a frequency of approximately 90 cycles/min with an amplitude of 3 cm. The temperature of the liquid methane gradually increased during the experiments due to the dissolution of the relatively warm nitrogen. The quantity of nitrogen which dissolved in the sloshing experiments ranged from 5.8 to 16.8 weight percent. The test in which 16.8 weight percent dissolved was conducted with liquid nitrogen spraying on the storage flask to prevent heating of the liquid methane during the dissolution process. The procedure enhanced the nitrogen solubilization process.

Experimental Results with Liquid Methane Gelled with

Water - The purpose of this series of experiments was to determine the quantities of water required to gel the liquid methane to such an extent that the nitrogen solubilization is less than 1 weight percent in liquid methane sub-cooled to 97°K (-284°F) under static conditions during one hour. In addition, the extent of nitrogen solubilization under sloshing conditions for five minutes is to be less than 3 weight percent. The storage flask in which the

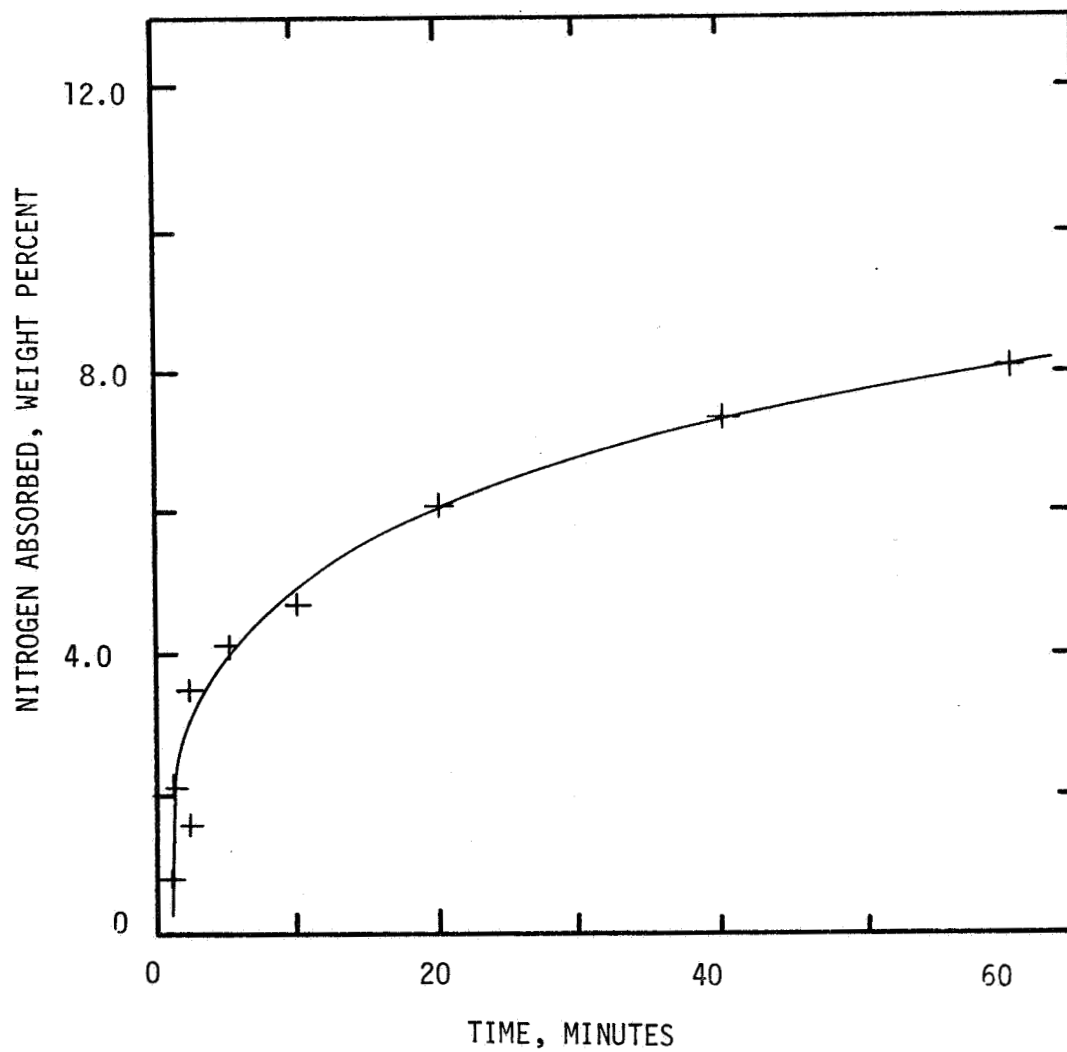


Figure 3. - Quantity of Nitrogen Dissolved in Ungelled Liquid Methane During a One Hour Storage Test at an Initial Temperature of 97°K (-284°F) vs Time

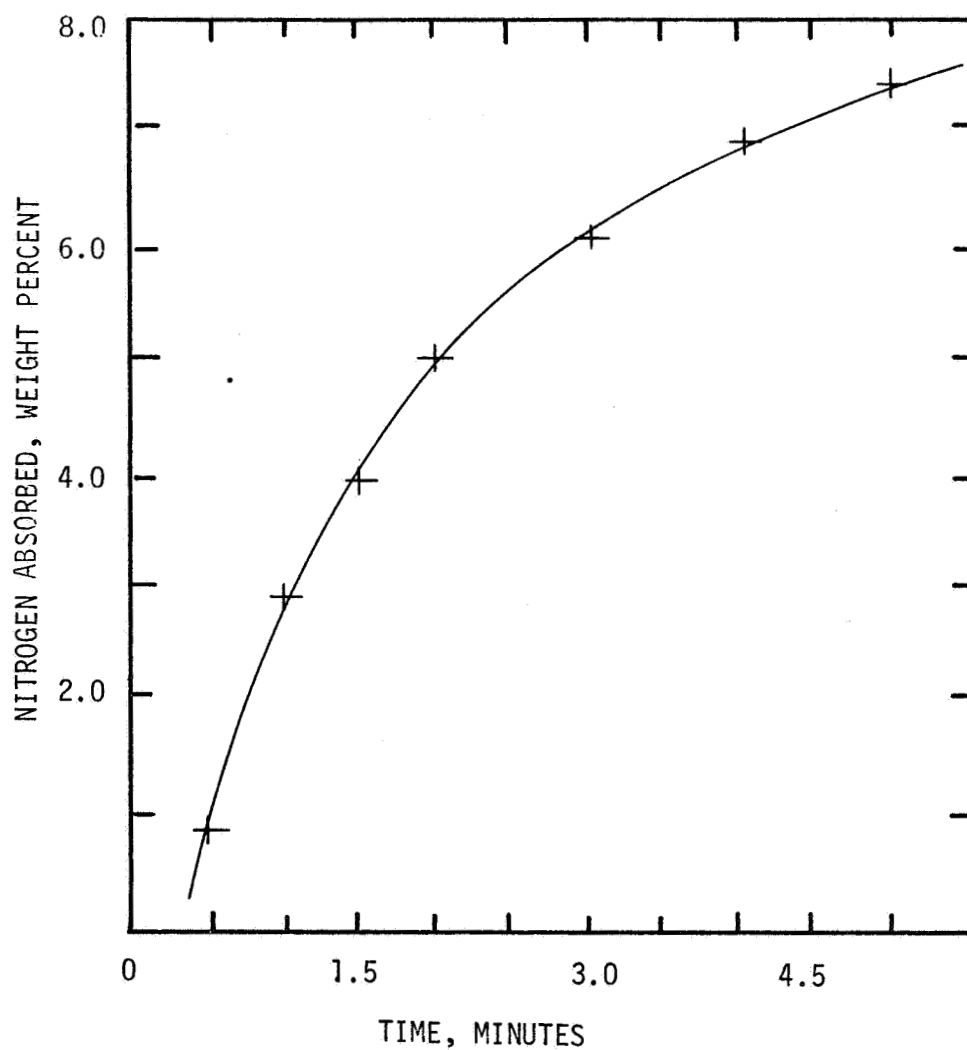


Figure 4. - Quantity of Nitrogen Dissolved in Ungelled Liquid Methane During Sloshing at an Initial Temperature of 97°K (-284°F) vs Time

experiments were conducted had a cross-sectional area of 18.12 cm^2 and, typically, 150 gm samples of gelled methane were used. This upper limit of the rates of nitrogen solubilization in liquid methane corresponds to $0.083 \text{ gm/cm}^2/\text{hr}$ under static conditions and approximates $0.9 \text{ gm/cm}^2/\text{min}$ under vigorous sloshing conditions.

The experiments were conducted using a 0.063 cm dia orifice in the heated injection tube and using methane as the carrier gas for the water vapor with a dilution ratio of carrier gas to water of 100:1 or greater. The liquid methane was maintained at various temperatures during the preparation to evaluate the best manner in which the experiments should be conducted. The gels were subcooled to the desired temperature prior to determination of the nitrogen solubilization rate in the liquid methane. A partial pressure of one atmosphere ($1.013 \times 10^5 \text{ N/m}^2$) of nitrogen was maintained over the gels during the experiments. The water content of the gel was measured by weighing the water remaining in the storage flask after the methane had been gradually distilled out of the apparatus at one atmosphere ($1.013 \times 10^5 \text{ N/m}^2$) pressure. The quantity of water injected into the system was also measured gravimetrically so that the capture efficiency of the injected stream in the liquid methane can be calculated.

The data which demonstrate the effectiveness of gelation of liquid methane by water for the inhibition of nitrogen solubilization are presented in Table III and are plotted in Figures 5 and 6. The significant items to be noted from the data are: (1) approximately 1 weight percent water particles in liquid methane is adequate to provide the gel structure necessary to inhibit the nitrogen solubilization rate during vigorous sloshing to less than 3 weight percent in five minutes, (2) less than 0.6 weight percent water particles in liquid methane is adequate to provide the gel structure necessary to inhibit the nitrogen solubilization rate during the static tests to less than 1 weight percent in one hour, (3) the gelant particles are similar whether prepared in a boiling liquid medium or in a subcooled liquid medium in which the carrier gas is completely condensed in the liquid phase; compare Experiments 29 and 30. The significance of the last item is that it infers that the gelled liquid methane can be made by direct injection through orifices of the appropriate mixture of water and methane vapor into a properly subcooled condensation apparatus without need for recycling or refluxing capability. This procedure was demonstrated to be feasible during the preparation of gelled liquid methane for the heat exchanger tests.

Experimental Results with Liquid Methane Gelled with Methanol - The purpose of this series of experiments was to determine the quantities of methanol required to gel the liquid methane with sufficient structure to meet the program goals as stated in the previous section. The same apparatus was used as described in the previous section. Both helium and methane were used as the carrier gas for the methanol and the carrier gas to methanol ratio was maintained at 100:1 or greater. The gas mixture was injected in both refluxing and subcooled liquid methane in order to obtain an indication

TABLE III. - DATA INDICATIVE OF THE SOLUBILIZATION RATE OF GASEOUS

NITROGEN IN LIQUID METHANE GELLED WITH WATER

Experiment Number	Gelant Concentration, Weight Percent	Gelant Preparative Conditions		Quantity of Gel, gm	Initial Temperature of Gel		Quantity of Nitrogen Absorbed			
		Methane Status	Carrier Gas		$^{\circ}\text{K}$	$^{\circ}\text{F}$	Static Test One Hour	Static Test Five Minutes	Static Test One Hour	Static Test Five Minutes
					gm	gm	gm	gm	gm	gm
							Wt%	Wt%	Wt%	Wt%
29	1.55	Boiling	CH ₄	161	99	-282	N.D.*	N.D.	0.90	0.56
30	1.53	Subcooled	CH ₄	157	99	-282	0.18	0.11	0.33	0.21
31	1.97	Subcooled	CH ₄	153	97	-285	N.D.	N.D.	0.30	0.19
44	0.98	Refluxing	CH ₄	173	97	-285	0.75	0.43	5.79	3.32
45	0.64	Refluxing	CH ₄	169	97	-285	0.86	0.51	7.95	4.69
46	1.42	Refluxing	CH ₄	169	97	-282	0.33	0.20	2.01	1.19
47	0.74	Refluxing	CH ₄	162	97	-284	0.75	0.46	6.87	4.23
48	0.94	Refluxing	CH ₄	171	97	-284	N.D.	N.D.	3.15	1.85

*N.D. indicates that the amount was not detectable.

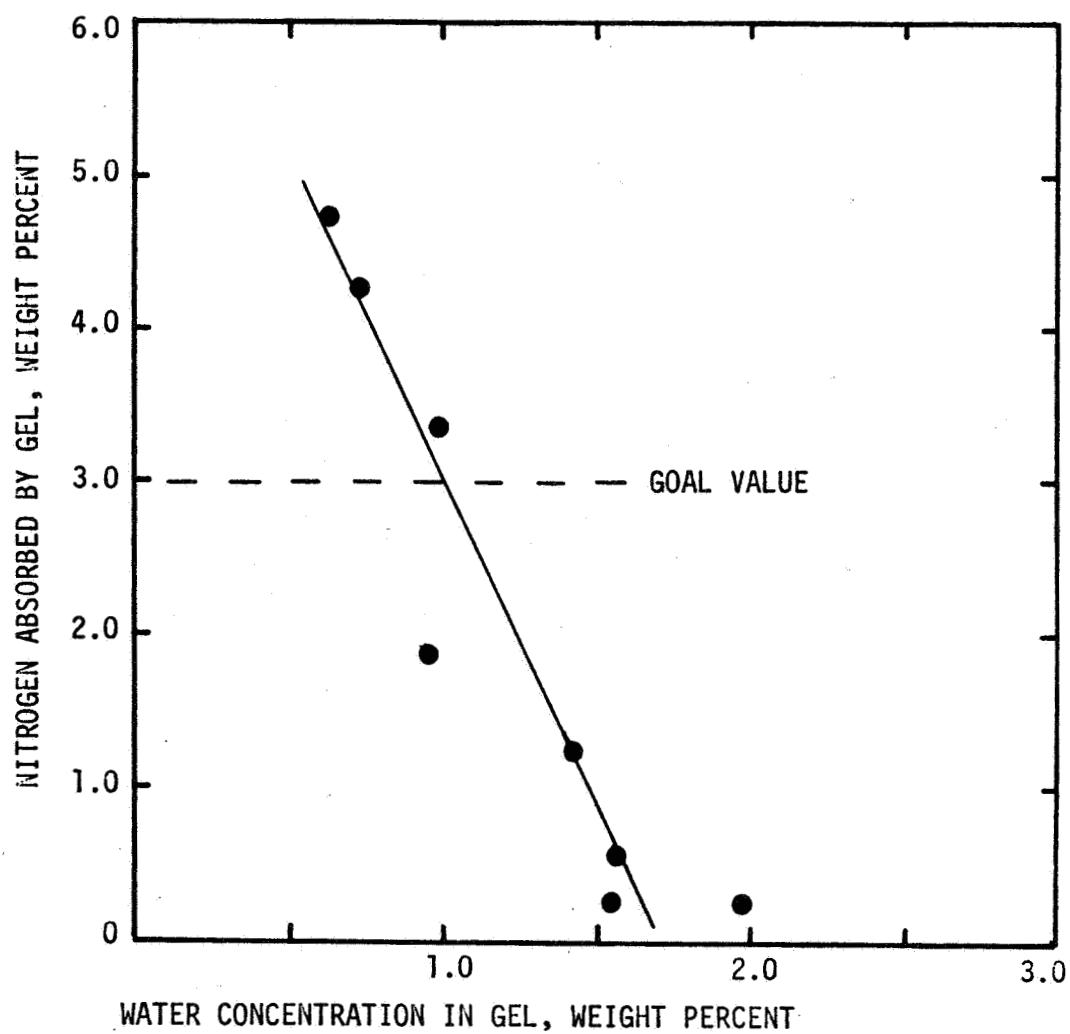


Figure 5. - Quantity of Nitrogen Absorbed by Gelled Methane During Five Minutes of Sloshing at 97°K (-284°F) vs the Concentration of Water in the Gel

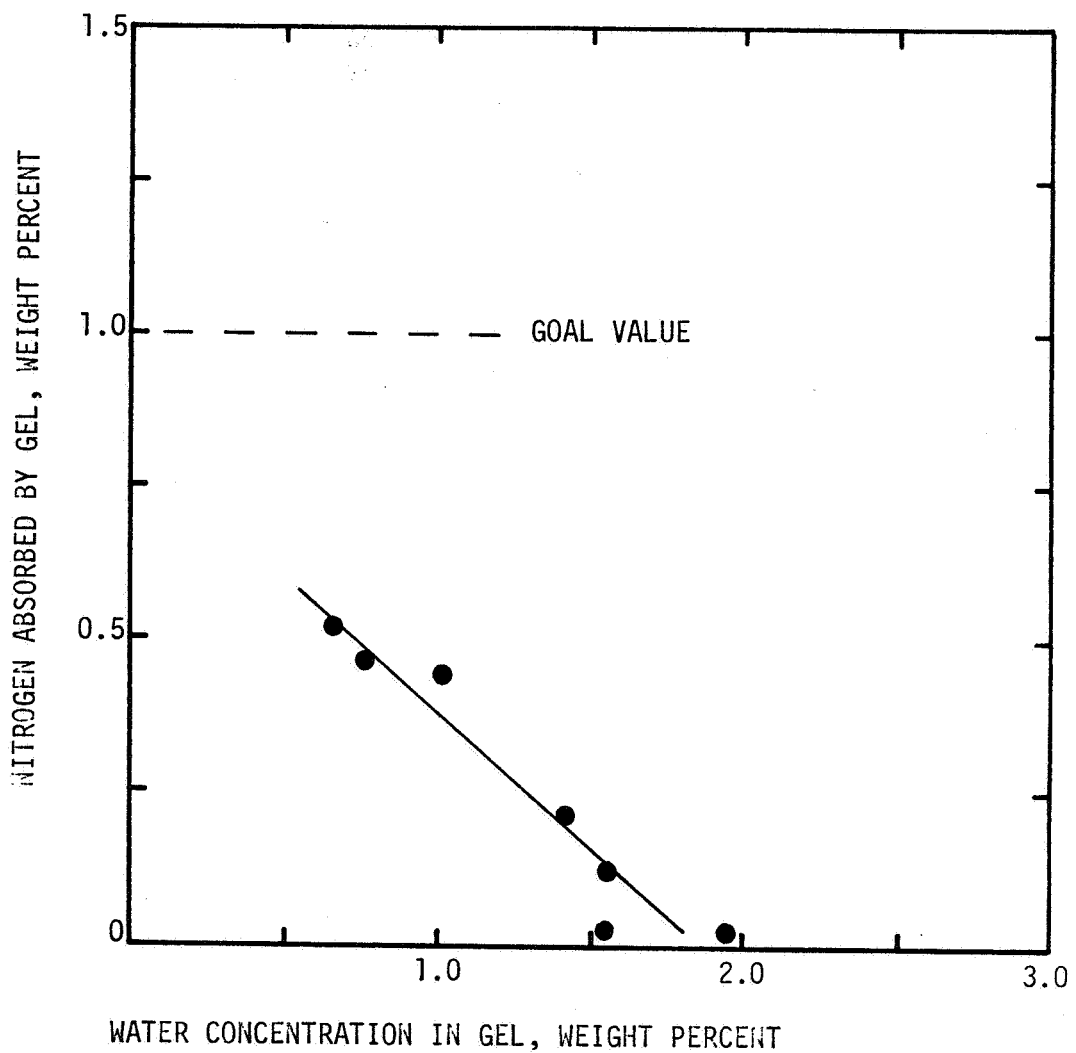


Figure 6. - Quantity of Nitrogen Absorbed by Gelled Methane in One Hour Under Static Conditions at 97°K (-284°F) vs the Concentration of Water in the Gel

of the optimum conditions for preparation of the gelant particles. The quantity of methanol in the gel was measured by weighing the methanol remaining in the storage flask after the methane had been gradually distilled out of the apparatus at one atmosphere ($1 \times 10^5 \text{ N/m}^2$) pressure. The quantity of methanol injected into the liquid methane was also determined gravimetrically.

The data which were obtained from this series of experiments are presented in Table IV and shown in Figures 7 and 8. The significant items to be noted from the data are: (1) approximately 1 weight percent methanol particles in liquid methane is adequate to provide the gel structure necessary to inhibit the nitrogen solubilization rate during vigorous sloshing to less than 3 weight percent in five minutes, (2) significantly less than 1 weight percent methanol particles in liquid methane is adequate to provide the gel structure necessary to inhibit the nitrogen solubilization rate during the static tests to less than 1 weight percent in an hour, (3) methanol particles prepared with helium as the carrier gas in place of methane are more effective in producing gel structure; compare the sloshing results from Experiment 34 with those of Experiment 38, and (4) injection of methanol vapor diluted with methane into the boiling liquid methane resulted in less gelling capacity of the methanol particles as compared with the particles prepared in subcooled liquid methane (Experiment 41 versus Experiment 38). The structure of the gels prepared with methane as the carrier gas for the methanol is not as reproducible as the gel structure obtained using helium as the carrier gas for the methanol.

b. Effect of Gel Aging on the Gaseous Nitrogen Solubilization Rate and the Sloshing Characteristics

The effect of aging on the gel structure in liquid methane was determined in the following manner. A batch of gel was prepared using water as the gelant, and the nitrogen solubilization rate was measured for the fresh gel in a one hour static test at 97°K (-285°F) as previously described. Then the gel was sloshed for five minutes at 90 cycles/min with an amplitude of 3 cm at 97°K (-285°F) in the apparatus previously described. After the sloshing test, the temperature of the gel was raised to approximately 108°K (-264°F) and maintained at this temperature level for 114 hr. The gel was subsequently cooled to 97°K (-285°F) and the static and sloshing tests repeated to determine the nitrogen solubilization rate.

The same test series was repeated with a gel prepared with methanol particles. The test results are presented in Table V. The data in Table V indicate that the gels do not undergo a prohibitive degree of degradation of gel structure. The data indicate that some loss of structure occurred in the gel prepared with water particles. In the sloshing tests, the nitrogen absorption was approximately fourfold greater with the aged gel than with the fresh gel. However, the higher rate remains well within the limits of acceptability. The data indicate an improvement of the gel structure in the gel prepared with methanol particles. However, it should be borne in mind

TABLE IV. - DATA INDICATIVE OF THE SOLUBILIZATION RATE OF GASEOUS
NITROGEN IN LIQUID METHANE GELLED WITH METHANOL

Experiment Number	Gelant Concentration, Weight Percent	Gelant Preparative Conditions		Quantity of Gel, gm	Initial Temperature of Gel		Quantity of Nitrogen Absorbed			
		Methane Status	Carrier Gas		$^{\circ}\text{K}$	$^{\circ}\text{F}$	Static Test One Hour	Static Test Five Minutes	Static Test One Hour	Static Test Five Minutes
				gm	$^{\circ}\text{K}$	$^{\circ}\text{F}$	gm	Wt%	gm	Wt%
34	2.5	Subcooled	He	154	97	-284	0.18	0.12	1.41	0.91
36	6.5	Subcooled	CH ₄	91	98	-283	0.18	0.20	2.66	2.93
38	2.6	Subcooled	CH ₄	154	100	-280	0.12	0.08	3.41	2.17
39	1.2	Subcooled	CH ₄	156	97	-284	0.09	0.06	7.72	4.71
40	1.1	Subcooled	He	156	98	-282	0.06	0.04	4.53	2.90
41	3.2	Subcooled	CH ₄	112	98	-283	0.21	0.19	6.90	6.14
49	2.1	Subcooled	He	155	98	-283	0.35	0.23	2.31	1.49
50	1.7	Subcooled	He	158	97	-284	0.51	0.32	2.79	1.77

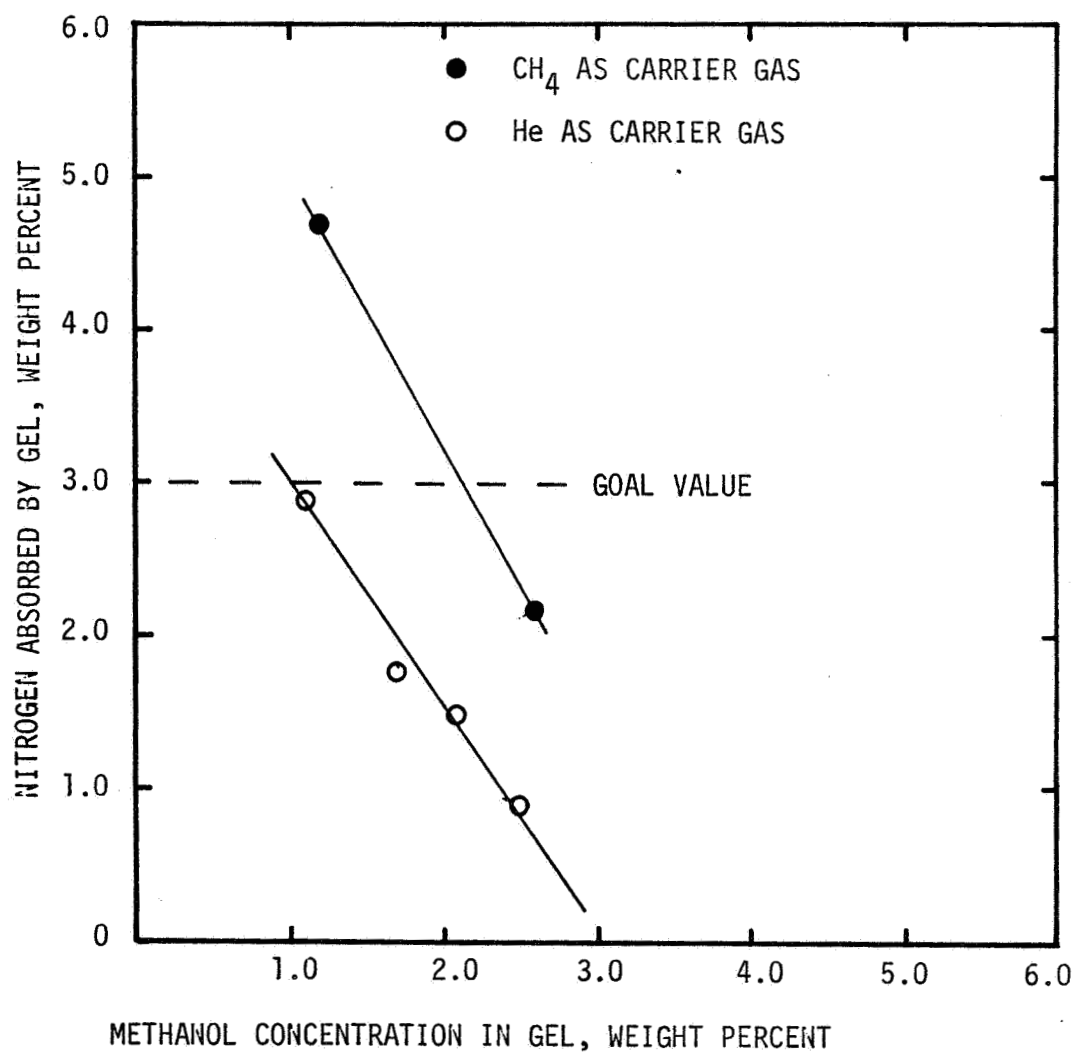


Figure 7. - Quantity of Nitrogen Absorbed by Gelled Methane During Five Minutes of Sloshing at 97°K (-284°F) vs the Concentration of Methanol in the Gel

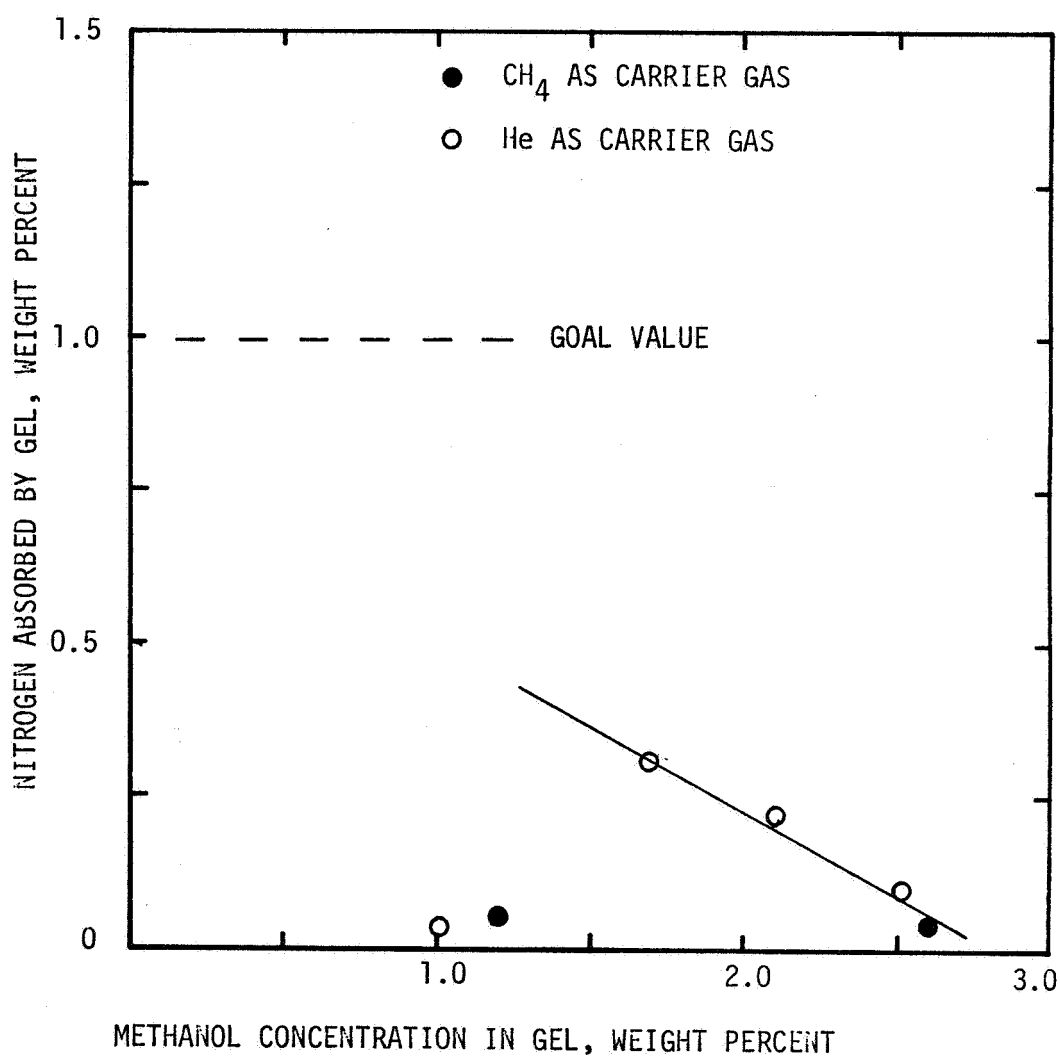


Figure 8. - Quantity of Nitrogen Absorbed by Gelled Methane in One Hour Under Static Conditions at 97°K (-284°F) vs the Concentration of Methanol in the Gel

TABLE V. - DATA INDICATIVE OF THE EFFECT OF AGING
ON THE GEL STRUCTURE OF LIQUID METHANE

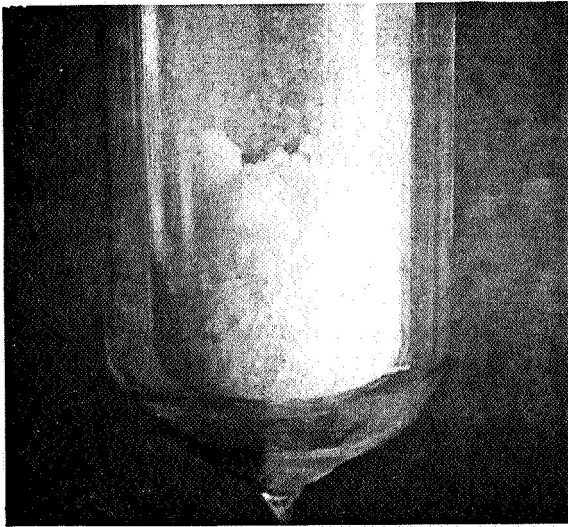
Gel Condition	Gelant Concentration, Weight Percent	Quantity of Gel, gm	Quantity of Nitrogen Absorbed			
			Static Test		Sloshing Test	
			gm	Wt%	gm	Wt%
Freshly Prepared	1.97% H ₂ O	153	N.D.*	N.D.	0.30	0.19
Aged for 114 hours	1.97% H ₂ O	153	0.72	0.47	1.11	0.72
Freshly Prepared	2.54% CH ₃ OH	154	0.18	0.12	1.41	0.91
Aged for 114 hours	2.54% CH ₃ OH	154	0.06	0.04	N.D.	N.D.

*N.D. indicates that the quantity was below the limits of detection.

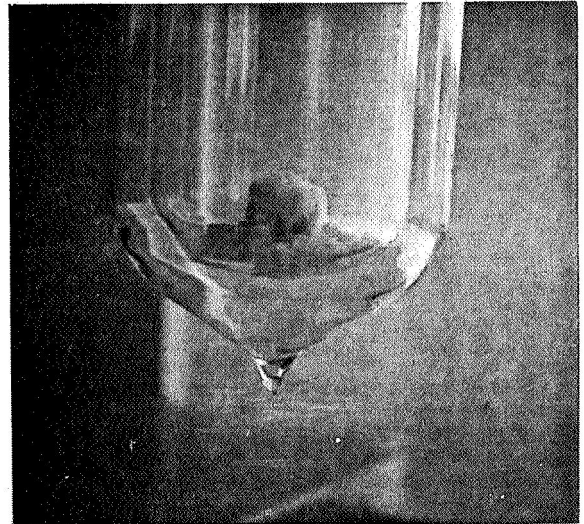
that the fresh gel prepared with methanol particles absorbed 1.03 weight percent nitrogen during the static and sloshing tests, and the surface of the aged gel already contained nitrogen during the second static and sloshing tests. On the basis of visual observation, there was no significant degradation of the gel structures in either case.

c. Effect of Gelation on the Venting Characteristics of the Fuel

Three types of tests were conducted to evaluate the venting behavior of liquid methane gelled with water particles. In the first test, approximately 600 cc of methane gelled with 2 weight percent water was transferred to a double-walled Pyrex flask initially at room temperature. The space between the two walls of the flask was evacuated and this allowed unimpaired visual observation of the gel as it evaporated. Four photographs at various stages of liquid methane boiloff are shown in Figure 9. The gel gradually withdraws from the walls of the vessel during the boiloff. Finally, only a pool of water is left.



APPEARANCE OF GEL AFTER
~50% BOILOFF OF METHANE



APPEARANCE OF GEL RESIDUAL
AFTER >90% BOILOFF OF METHANE



APPEARANCE OF GEL RESIDUAL
AFTER >90% BOILOFF OF METHANE



APPEARANCE AFTER 100%
BOILOFF OF METHANE

Figure 9. - Behavior of Gelled Methane as Methane Boiloff Progresses

The second test involved the transfer of liquid methane, gelled with water, from the preparation flask through coils of Teflon tubing with a 0.25 cm internal diameter. The first coil, 206 cm long, was submerged in gelled liquid methane; the second coil, 155 cm long, was immersed in an ice-water bath so that the methane would completely vaporize; and the third coil, 262 cm long, was immersed in a Dry-Ice/methanol bath which should trap significantly agglomerated ice particles. The total length of the transfer tube was 793 cm. With a driving pressure of $3.4 \times 10^4 \text{ N/m}^2$ (5 psi), approximately 200 cc of liquid methane gelled with 1.5 weight percent water was passed through the coils and vented to the atmosphere with no restrictions in flow being detected. A photograph of the test apparatus is shown in Figure 10.

The third test involved an attempt to photograph the behavior of gelled methane as it is transferred into a warm surface. The gel vaporized immediately on contact with the warm surface and there was nothing but a vapor cloud to photograph.

d. Effect of Gelant Concentration on Expulsion Efficiency and Sloshing

A series of experiments was conducted to determine the effect of evaporation on the expulsion efficiency of methane gelled with water and gelled with methanol. The nominal levels of boiloff to be evaluated were 0, 5, 30, 50, and 90 percent. In addition to the expulsion characteristics, the sloshing behavior of the evaporated gels was also evaluated.

The same apparatus was used for the experiments as for the nitrogen solubilization measurements. The following procedure was used. Approximately two liters of gel were prepared in the usual manner. A sample of the gel was transferred from the preparation flask to the storage flask. The sample in the storage flask was then subjected to the sloshing action and then the sample in the storage flask was analyzed for the gelant concentration. The gel in the preparation flask was warmed sufficiently to cause 5 percent boiloff of the methane from the gel and then a sample was transferred to the storage flask. The sample was sloshed and analyzed. The residual gel in the preparation flask was then warmed again to evaporate an amount of methane corresponding to 30 percent boiloff of the methane. Again a sample was transferred, sloshed, and analyzed. The procedure was repeated to produce a gel with 50 percent boiloff. At this point, insufficient gel remained to allow 90 percent boiloff. A fresh batch of gel was prepared at a higher gelant concentration and evaporated to such an extent that the gelant concentration corresponded to approximately that which would be produced by 90 percent boiloff from the first batch of gel. The value of the surface area to volume ratio of the preparation flask used in these experiments was approximately one.

The expulsion efficiency was determined in the following manner. The gel level in the preparation flask was measured; then the sample of gel was transferred to the storage flask and the volume in the storage flask

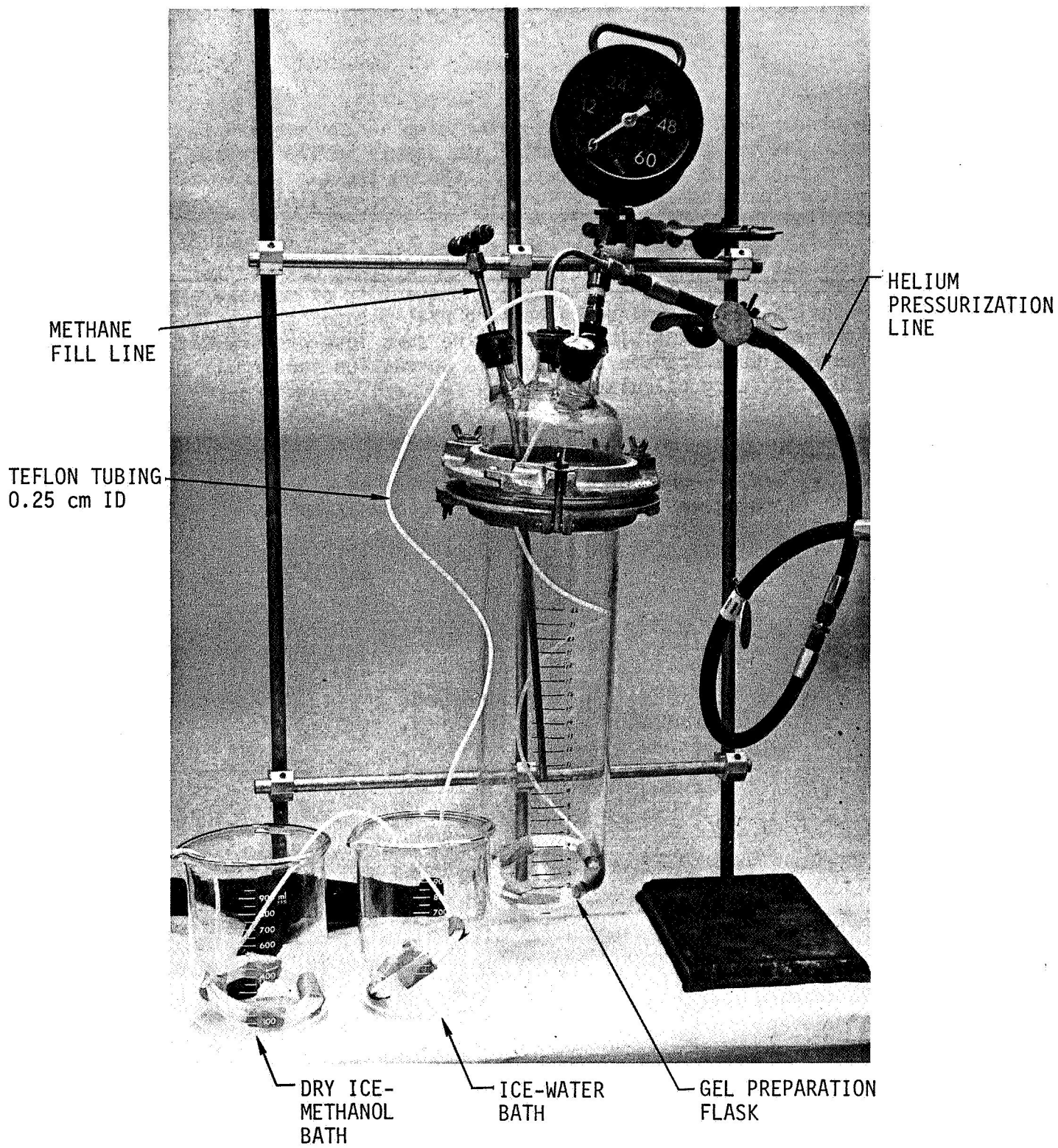


Figure 10. - Apparatus for Evaluating Potential Problems During Transfer of Gel

was measured. The level of the gel remaining in the preparation flask then was measured. The value of the volume of the sample in the storage flask was divided by the value of the difference between the two levels of gel in the preparation flask and the resulting fraction was multiplied by 100 to give a percent value for expulsion efficiency. To transfer the gels from the preparation flask to the storage flask, it was necessary to pass the gel through a valve that was external to the constant-temperature box and this resulted in vaporization of some of the methane. The quantity of methane vaporized by this operation was determined by passing neat methane through the transfer system and measuring the liquid loss. The same loss was assumed to occur while the gels were transferred and this correction factor was applied to the expulsion efficiency calculations.

During the sloshing portion of the test, the average distance which the gel moved on the surface of the storage flask was noted and these values are presented as "displacement of gel surface during sloshing." The sloshing was conducted at a frequency of approximately 100 cycles/min. The data are presented in Table VI.

TABLE VI. - DATA INDICATIVE OF THE EXPULSION EFFICIENCY OF GELLED METHANE

Gelant, Wt%		Boiloff, Percent	Expulsion Efficiency, Percent	Displacement of Gel Surface During Sloshing, ± cm
H ₂ O	0.8	0	100	1.4
		5	100	0.8
		37	82	0.5
		60	84	0.3
H ₂ O	7.1	89*	Gel cored	---
CH ₃ OH	2.7	0	100	0.8
		6	93	0.3
		34	100	0.5
		52	87	Not apparent
CH ₃ OH	7.2	83**	86	Not apparent

*Calculated boiloff value based on initial value of 0.8%.

**Calculated boiloff value based on initial value of 1.2%.

The significant items to be noted from the data are that (1) at comparable gelant concentrations, methane gelled with methanol particles has less tendency to adhere to surfaces than the methane gelled with water, (2) as the gelant concentration increases due to boiloff, the tendency for displacement during sloshing decreases, and (3) after subjection to severe boiloff conditions, the gels are still transferable. The methane gelled with water at the 7.1 weight percent level experienced coring during the attempted transfer. However, in an apparatus with a better geometric configuration for a transfer operation, the material could have been transferred. The displacement of the methane gelled with methanol at the high boiloff value was not apparent during sloshing because of the opacity of material adhering to the storage flask walls.

e. Discussion of Results

Gelation of the liquid methane with either water or methanol particles dramatically reduces the rate at which gaseous nitrogen is absorbed by liquid methane subcooled to 97°K. A typical nitrogen absorption rate for ungelled liquid methane at 97°K and one atmosphere ($1.013 \times 10^5 \text{ N/m}^2$) partial pressure of nitrogen is 3 gm/cm² of surface/hr; while with 1 weight percent water as gelant, the value is reduced to 0.034 gm/cm²/hr; and with 1 weight percent methanol as gelant, the value is reduced to 0.045 gm/cm²/hr. The rate values are reduced to essentially zero by increasing the water gelant concentration to 1.95 weight percent or by increasing the methanol gelant concentration to 2.9 weight percent. The data for water are presented graphically in Figure 11, and the data for methanol are presented graphically in Figure 12.

The equation for the rate of nitrogen solubilization at 97°K in liquid methane gelled with water particles over the range from 0.5 to 1.95 weight percent is as follows:

$$\text{Rate (gm N}_2\text{/cm}^2 \text{ of gel surface/hr)} = 0.036 [P_{N_2}] [1.95 - C_w]$$

where P_{N_2} = partial pressure of N_2 in atmospheres,

and C_w = concentration of water in weight percent.

The analogous equation for the rate of nitrogen solubilization at 97°K in liquid methane gelled with methanol particles over the range from 1.0 to 2.9 weight percent is as follows:

$$\text{Rate (gm N}_2\text{/cm}^2 \text{ of gel surface/hr)} = 0.024 [P_{N_2}] [2.9 - C_{me}]$$

where P_{N_2} = partial pressure of N_2 in atmospheres,

and C_{me} = concentration of methanol in weight percent.

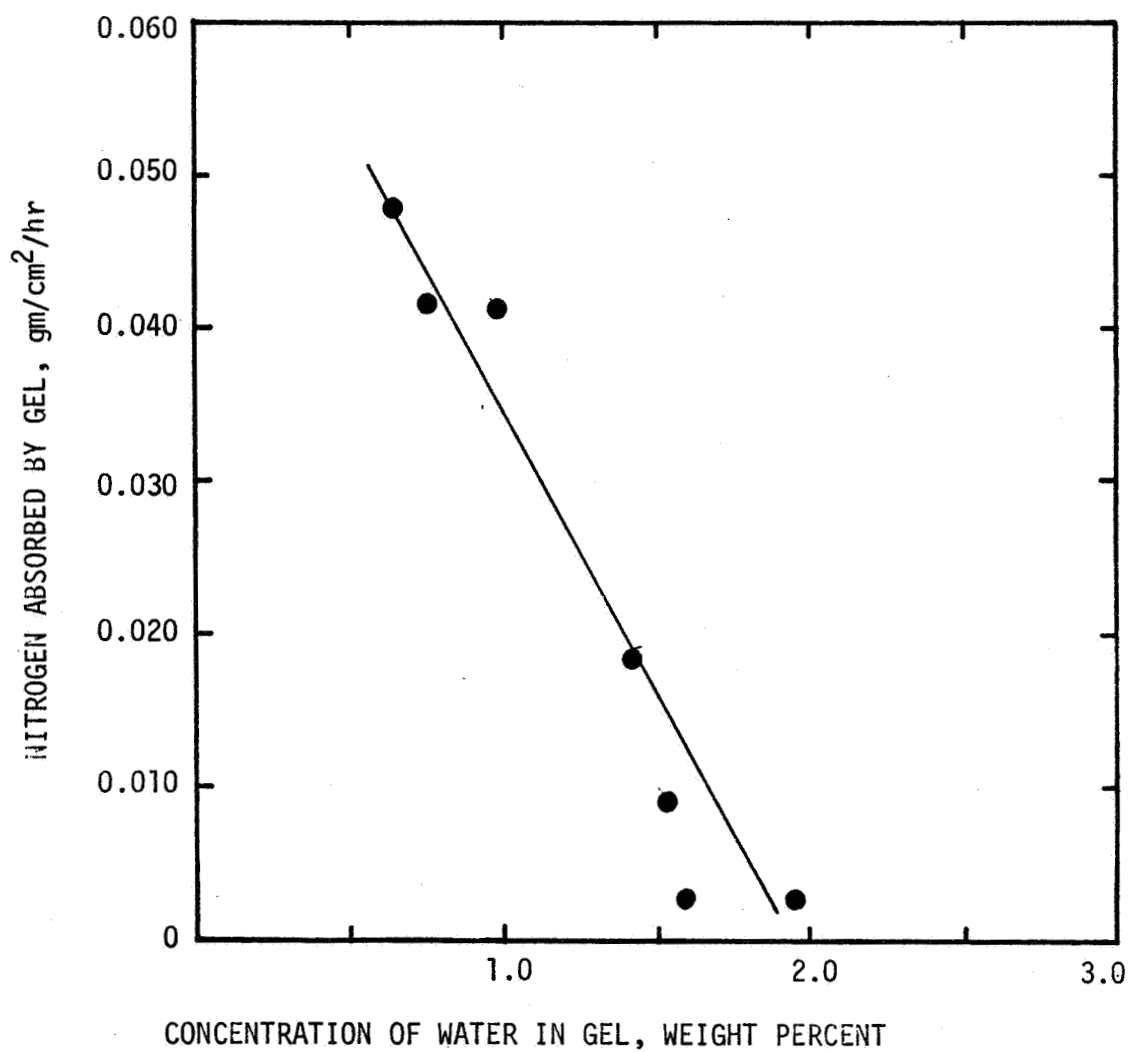


Figure 11. - Rate of Nitrogen Absorption vs Gelant Concentration in Liquid Methane at 97°K (-284°F)

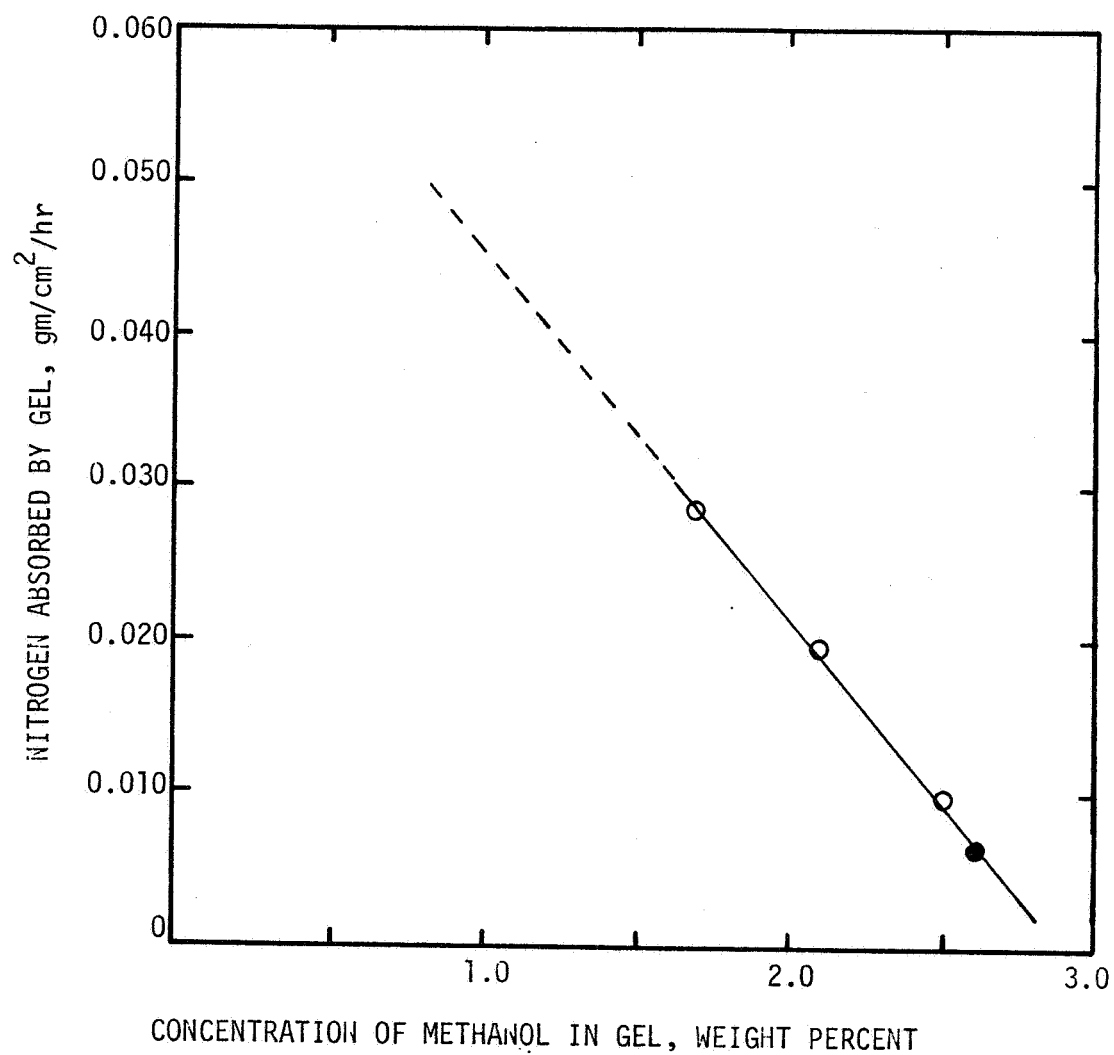


Figure 12. - Rate of Nitrogen Absorption vs Gelant Concentration in Liquid Methane at 97°K (-284°F)

Under violent sloshing conditions, the rate of nitrogen solubilization is greatly accelerated as compared with the static tests, but the data indicate that 1 percent gelant of either methanol or water is adequate to meet the program goal.

Based on the available characterization data, both methanol and water particles are suitable gelants for liquid methane. The advantages of using water are:

- (1) Ease of preparation - Methane is a suitable carrier gas for preparation of the gelant particles and no recycling facility is required.
- (2) Cost - Distilled water is one of the most inexpensive compounds available.

The disadvantages of using water are:

- (1) No fuel value - Approximately 1 percent less total fuel value due to gelation.
- (2) Expulsion efficiency - At the high gelant concentrations, greater than 5 weight percent, the liquid methane gelled with water adheres more tenaciously to vessel walls than the liquid methane gelled with methanol.

The advantages of using methanol as the gelant for liquid methane are:

- (1) Fuel value - Methanol has a fuel value about one-half that of methane, and gelation causes approximately a 0.5 percent loss in total fuel value.
- (2) Expulsion efficiency - Liquid methane gelled with methanol does not adhere to surfaces as tenaciously as liquid methane gelled with water.

The disadvantage of using methanol as the gelant for the liquid methane as compared to water as the gelant is:

Preparative procedure - Helium is the required carrier gas, a recycling system is necessary to recover helium and methane from the process, and the preparation process is more complex.

The results of the experiments are very encouraging and the data demonstrate that liquid methane gelled with water particles and gelled with methanol particles warrant further extensive investigation in heat exchanger tests.

B. HEAT EXCHANGER TESTS

The purpose of the heat exchanger tests is to evaluate the handling characteristics of gelled methane with regard to potential problems that might arise in the fuel acquisition system. Potential problems which may arise during transfer of the fuel from tanks to the engines are: (1) clogging of the heat exchangers by gelant materials, (2) formation of solid materials, such as methane hydrates, under temperature and pressure conditions typically encountered in heat exchangers, and (3) variation of gelled fuel characteristics during the transfer through the fuel acquisition system.

The discussion of heat exchanger tests is presented under four headings: (1) Experimental Apparatus, (2) Experimental Procedures, (3) Experiment Results, and (4) Discussion of the Results.

1. Experimental Apparatus

The basic guidelines established for the design of the heat exchanger apparatus were as follows:

FUEL: Methane containing less than 5 weight percent water or methanol as gelling agent

FUEL FLOW RATE: 4.5 kg/hr (10 lb/hr)

FUEL FEED PRESSURE: $7.93 \times 10^5 \text{ N/m}^2$ (115 psia)

HEAT FLUXES IN HEAT EXCHANGER: 15,760 to 63,040 W/m^2
(5,000 to 20,000 Btu/hr-ft²)

THREE SECTIONS IN HEAT EXCHANGER:

Section 1: Raise temperature of fuel from 3°K (5°F) below its normal boiling point to 144°K (-200°F); i.e., from 108°K (-265°F) to 144°K (-200°F).

Section 2: Raise temperature of fuel vapor from 144°K (-200°F) to 1°K (2°F) below the melting point of the gelant; i.e., from 144°K (-200°F) to 272°K (+30°F) if water is gelant and from 144°K (-200°F) to 174°K (-147°F) if methanol is gelant.

Section 3: Raise temperature of methane vapor to 297°K (75°F).

The power requirements necessary to meet the guidelines are given in Table VII.

TABLE VII. - POWER REQUIREMENTS FOR THE THREE SECTIONS
OF THE HEAT EXCHANGER

Fuel	Heat Exchanger Section	Temperature Range		Power Requirement, Watts		
		°K	°F	CH ₄	H ₂ O	CH ₃ OH
95 wt% CH ₄ /5 wt% H ₂ O	1	108 to 144	-265 to -200	674.4	2.4	-
	2	144 to 272	-200 to +30	351.1	13.1	-
	3	272 to 297	+30 to +75	67.3	27.5	-
95 wt% CH ₄ /5 wt% CH ₃ OH	1	108 to 144	-265 to -200	674.4	-	3.6
	2	144 to 174	-200 to -147	88.9	-	4.8
	3	174 to 297	-147 to +75	329.5	-	23.8

The heat exchanger was designed and constructed in the following manner. The heat exchanger tubes were made of 0.48 cm (3/16 in.) OD x 0.081 cm (0.032 in.) wall, Type 304 stainless-steel tubing. The tubes were cut to length [two 96 cm (38 in.) and one 36 cm (14 in.)] and fitted with 0.635 cm (1/4 in.) flared-tube adapters for connection to the headers. Two 0.10 cm (0.040 in.) dia holes were drilled 5.1 cm (2 in.) from the inlet and outlet ends of the tubes. Bare junction thermocouples, prepared from 0.10 cm (0.040 in.) OD sheathed chromel/alumel thermocouple stock, were brazed in the tubes so that the exposed junction was approximately on the tube centerline for measurement of bulk fluid temperature. Two thermocouples were also spot-welded to the outside of the tube at its center for measurement of the tube wall temperature.

Each tube, with thermocouples installed, was wrapped with a single layer of woven glass tape [0.020 cm (0.008 in.) thickness]. A 0.16 cm (1/16 in.) thick layer of ceramic cement was applied. After the cement had dried, nichrome-wire heating element was wound uniformly on the tube to within 2.5 cm (1 in.) of the tube ends. The characteristics of each tube are presented in Table VIII. Another layer of ceramic cement, 0.16 to 0.32 cm (1/16 to 1/8 in.) thick, was applied over the heating element and dried to hold the element winding in place and to provide insulation. The tube was then wrapped with a layer [approximately 0.32 cm (1/8 in.) thick] of asbestos and finally the tube was wrapped with a ceramic fiber blanket and inserted into a 2.5 cm (1 in.) ID aluminum tube.

TABLE VIII. - HEAT EXCHANGER TUBE CHARACTERISTICS

Tube Section	Overall Tube Length,		Heater Element Wire Diameter		Heater Element Total Resistance*, ohms	Power Output, watts
	cm	in.	cm	in.		
1	96	38	0.10	0.040	9	1100 at 100v
2	96	38	0.05	0.020	29	350 at 100v
3	36	14	0.04	0.016	20	125 at 50v

*At ambient temperature.

The heat exchanger components, including the three heating sections and the three headers, were assembled on a support framework for installation in the temperature-conditioning box. After assembly, the heating sections were further insulated with 2.5 cm (1 in.) pipe insulation. A schematic diagram of the heat exchanger is shown in Figure 13; a photograph of the assembled heat exchanger is shown in Figure 14.

The heat exchanger headers consist of 2.5 cm (1 in.) OD x 0.165 cm (0.065 in.) wall x 10.2 cm (4 in.) long, Type 304 stainless-steel tubing, attached to the heater sections by means of machined fittings. Transparent windows [2.5 cm (1 in.) dia x 0.0635 cm (0.025 in.) thick] are mounted in the header end-fittings to permit observation of the fluid phases in the header; pressure taps are provided in the end-fittings; and the end-fittings are machined to hold filter screens for evaluation of the deposition characteristics of the gelant material in the filters. A diagram of the header section is shown in Figure 15.

Pressure transducers are connected to the pressure taps by means of 0.32 cm (1/8-in.) OD tubing. All transducers are mounted rigidly to the support framework in such a way that the transducers are external to the temperature-conditioning box when the framework is installed. All electrical connections and thermocouple connections to instrumentation cables are made outside the temperature-conditioning box.

When the heat exchanger assembly is installed in the temperature-conditioning box, the No. 1 and No. 2 header assemblies are situated just behind Plexiglass viewing ports. Small lamps are mounted at the inboard windows of these two headers to assist the observation of the flow phenomena in the header. The exit end of the third tube and the third header are situated outside the box.

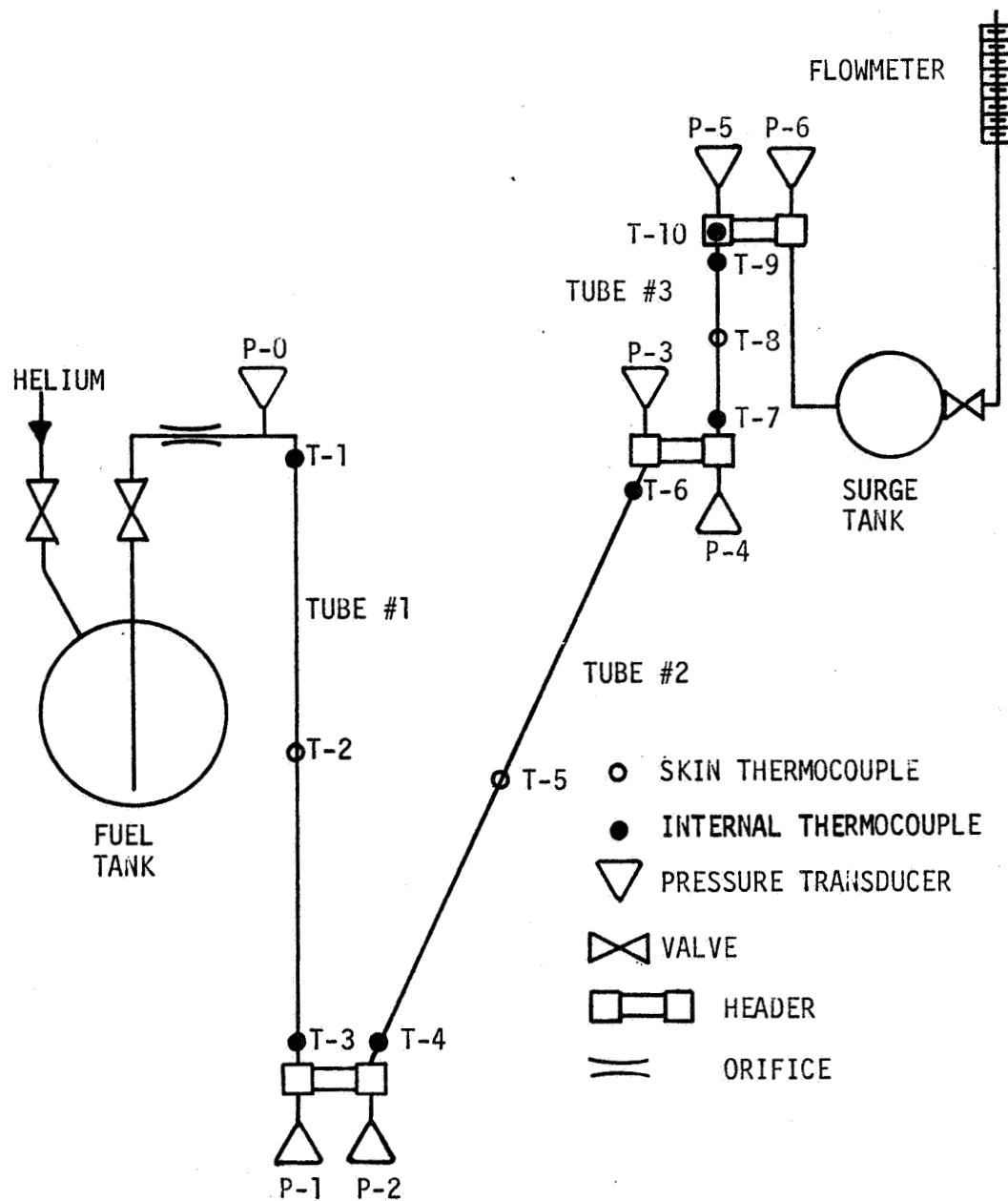


Figure 13. - Schematic Diagram for Heat Exchanger During Tests

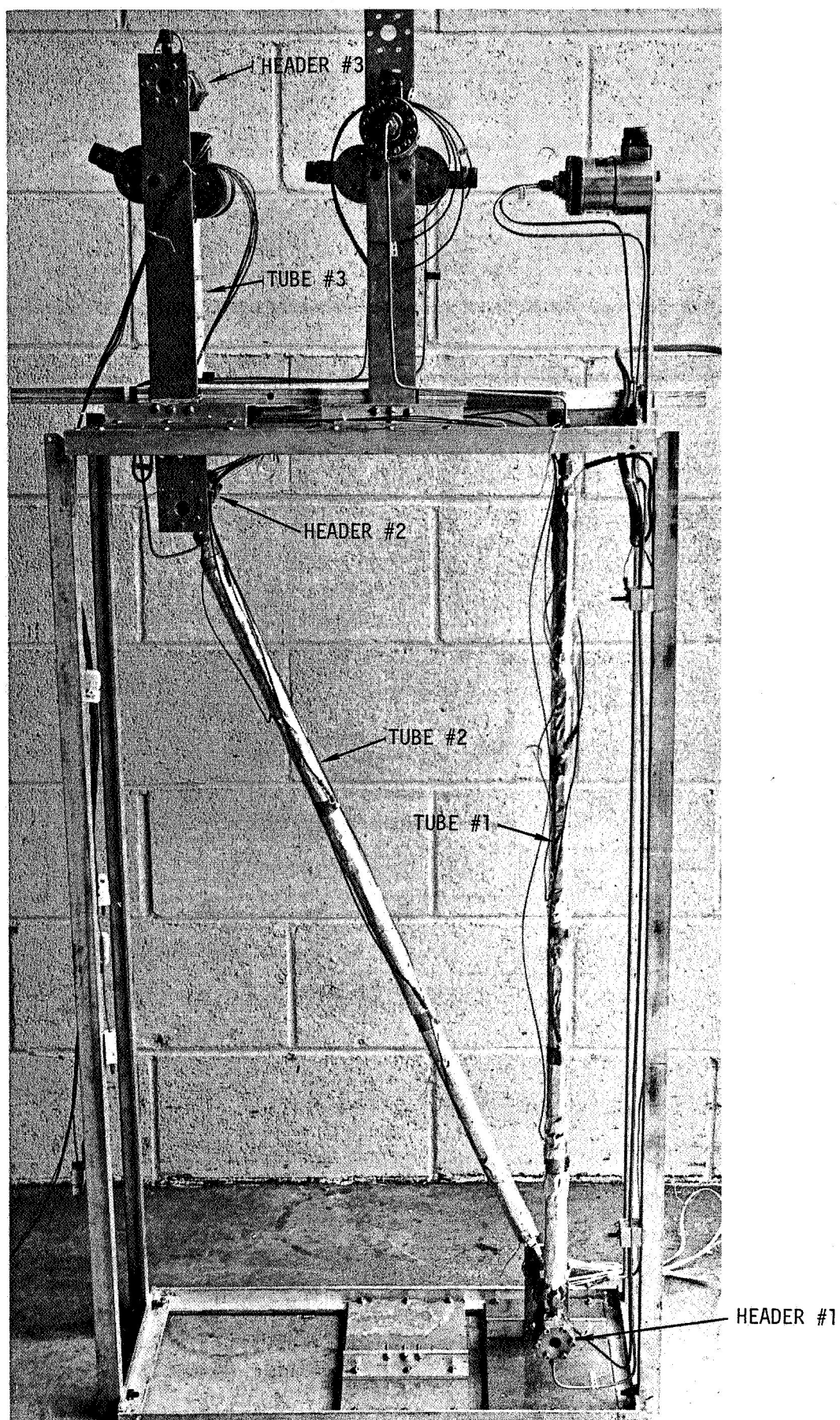


Figure 14. - Assembled Heat Exchanger

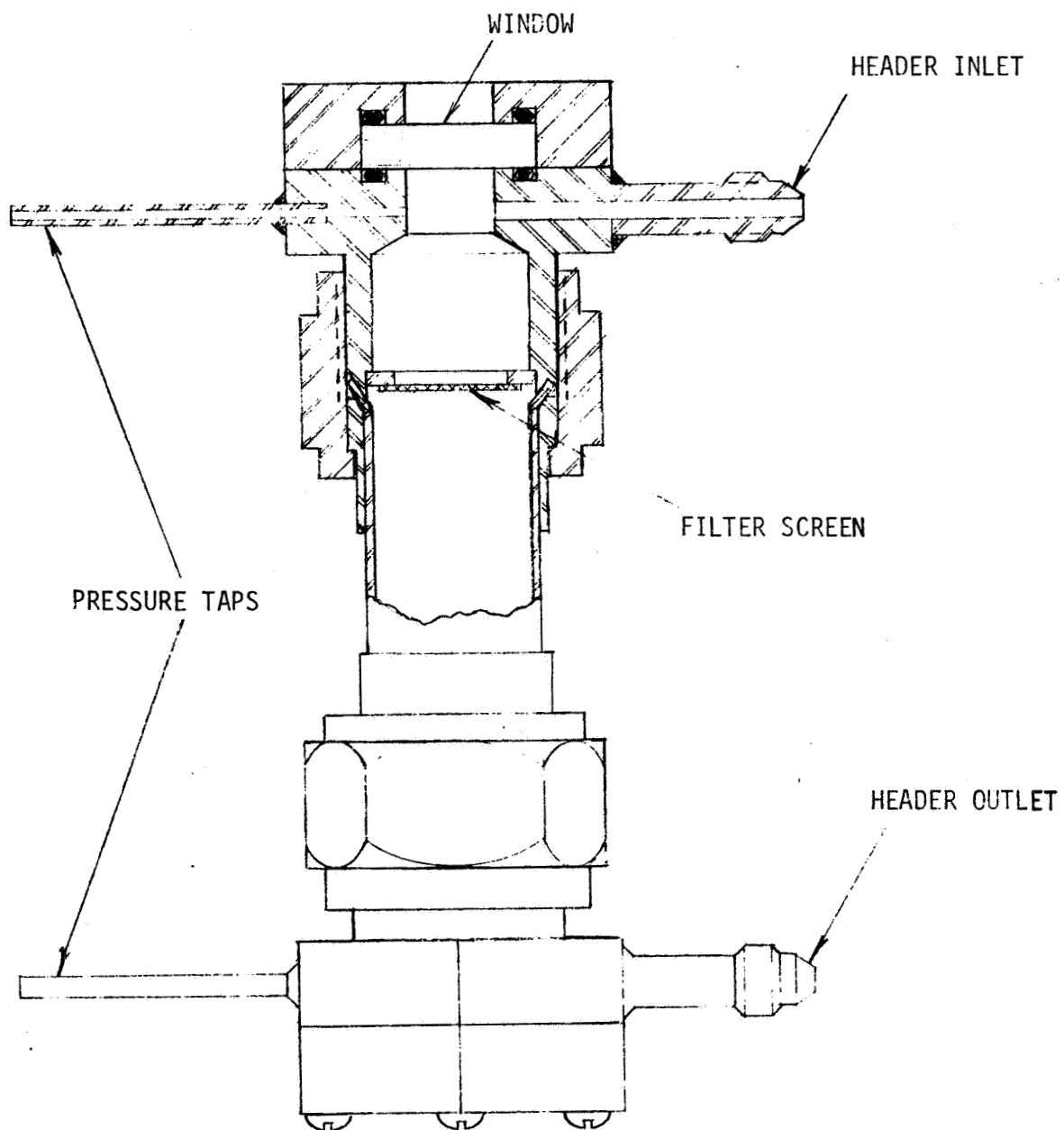


Figure 15. - Gelled Methane Heat Transfer Apparatus
Heat Exchanger Header Assembly

Downstream of the third header is a 300 cc stainless-steel cylinder fitted with a flow control valve at the exit end. The tank serves as a surge tank to dampen small pressure variations in the heat exchanger and the valve is used to regulate the flow through the heat exchanger. The gaseous methane from the heat exchanger is discharged through a flowmeter into a high-capacity exhaust hood.

The gelled fuel was supplied to the heat exchanger from a 20-gal stainless-steel tank which was fitted with turbine-type mixer blades for final mixing of the fuel. In addition, the tank was equipped with a thermocouple to monitor the fuel temperature, a regulated helium supply for pressurization of the fuel tank, and transfer lines for filling and emptying the fuel tank.

The heat exchanger apparatus, the fuel tank, and the gel preparation apparatus were all contained in the same constant-temperature box. A photograph of the interior of the box is shown in Figure 16.

2. Experimental Procedures

a. Method of Gelled Methane Preparation

Preliminary experiments were conducted to define the manner in which the larger batches of gel should be prepared. As a result of the experiments, the gel was prepared in a six-liter flask using the same hardware as used for the two-liter batches. The gaseous methane was initially condensed in the flask until the liquid level covered the orifice of the injection tube. An appropriate mixture of gaseous methane and water vapor was passed through the heated injection tube so that the desired water concentration is attained in the gel when five liters of methane have accumulated in the flask. An internal cooling coil that contained liquid nitrogen was used to condense the methane in the flask and allowed the preparation procedure to be conducted in a closed system.

The batches of gel were transferred through 0.95 cm (3/8 in.) OD tubing into the fuel tank for the heat exchanger. A 16-mesh screen was used to filter the gel during the transfer and approximately $6.89 \times 10^4 \text{ N/m}^2$ (10 psi) of helium driving pressure was used during the transfer. Under these conditions, the flow rate of the gel was approximately four liters/min. After sufficient gel had been prepared to conduct a test with the heat exchanger, the gel was stirred in the fuel tank by means of turbine mixer blades which were driven externally by an air motor.

b. Heat Exchanger Operation

The fuel tank was connected to the heat exchanger by means of 0.635 cm (1/4 in.) OD tubing. A 0.079 cm (0.031 in.) orifice was placed in the transfer line initially as a means of checking the flow rate by

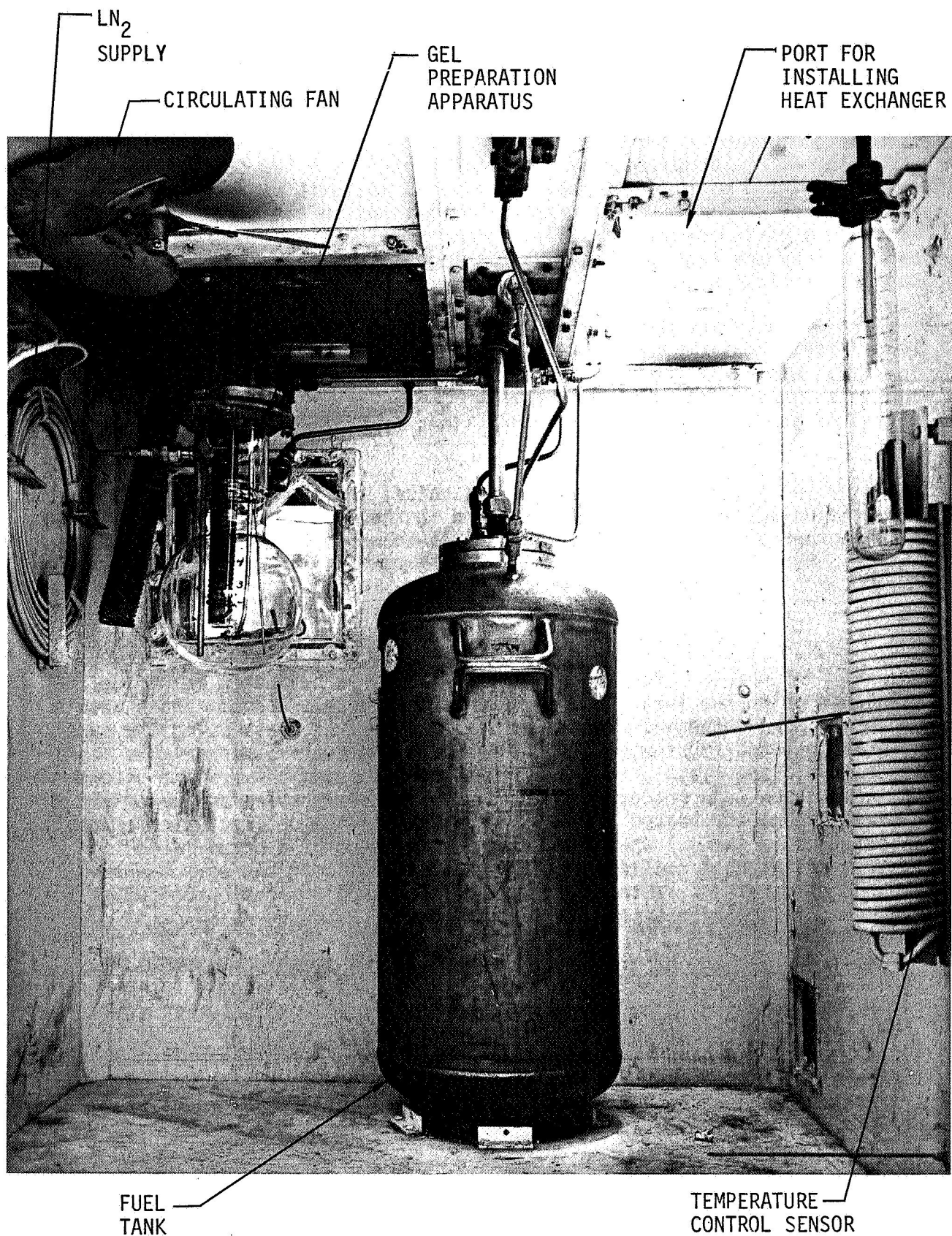


Figure 16. - Interior of the Constant Temperature Box
Used for Heat Exchanger Tests

pressure drop measurement. However, the pressure drop value through the orifice was approximately $6.9 \times 10^3 \text{ N/m}^2$ (1 psi) which was insufficient for accurate flow measurement; therefore, the flow measurements were made with the flowmeter at the exit of the heat exchanger apparatus. Prior to the test, helium was passed through the heat exchanger while the tubes were heated to the desired temperature levels. Finally, the gelled methane flow was initiated and the pressure and temperature data were recorded on a direct writing oscillograph and taped for later reduction by a computer system. The heat exchanger was operated in the above sequence to avoid filling the header sections with gelled methane before adequate power was available to vaporize the methane.

During the heat exchanger operation, the header sections were monitored visually and the power inputs were varied to define the stable operating conditions.

3. Experimental Results

Five tests were conducted with liquid methane gelled with varying quantities of water as the gelant. The desired conditions in the heat exchanger operation were as follows: (1) Section 1 should raise the fluid temperature from 3°K (5°F) subcooled to a condition in which the methane is fully vaporized but only slightly superheated; (2) Section 2 should raise the fluid temperature to approximately 1°K (2°F) below the melting point of the gelant; (3) Section 3 should further raise the fluid temperature to 297°K (75°F). Prior to the start of the methane flow through the heat exchanger, the fuel tank was pressurized to $8.6 \times 10^5 \text{ N/m}^2$ (110 psig) with helium. Before the gelled methane tests were conducted, an initial checkout test was conducted with liquid methane itself. Each test is described below.

a. Heat Exchanger Test 1

The purpose of the first heat exchanger test with gelled methane was to demonstrate that the ice particles can be transported through representative tubes and header sections without difficulty. No screens were placed in the header sections for this experiment. At the initiation of the test, the heater for the third heating tube section failed. Consequently, the test was conducted at a reduced flow rate of 2.27 kg/hr (5 lb/hr). Within one minute after initiation of flow, the liquid methane covered the windows in the first header and they remained opaque throughout the test. The test progressed satisfactorily for 90 min, at which time the test was stopped to investigate an erratic pressure reading at the entrance to the second header. Evidently, an ice plug formed in the unprotected line to the transducer. After flushing the system with helium, the flow of gelled methane was again initiated and continued for 15 min, at which time the test was terminated. The significant item to be noted from the test is that the gelled methane with 1.7 weight percent was transferred through the heat exchanger at the reduced flow rate of 2.27 kg/hr (5 lb/hr).

b. Heat Exchanger Test 2

The purpose of the second test was to identify potential problem areas in passing gelled methane through representative heat exchanger tubes, headers, and screens. In this test, liquid methane, gelled with 1.9 percent water, was used. Filter screens [20 mesh, 0.084 cm (0.033 in.) opening] were installed in each of the headers prior to the test. Test 2 can be conveniently divided into four sections based on the values of the operating parameters.

Section 1: During the initial 12 to 13 min, the methane flow was 2.5 kg/hr (5.5 lb/hr). The flow rate was then increased to 3.4 kg/hr (7.5 lb/hr) for about 7 min until a large ΔP began to develop between P_1 and P_2 , indicating fouling of the screen in Header 1. The fouling was removed by passing helium through the system. The pressure data for this section of the test are shown in Figure 17 as the 0 to 2400 sec segment. The number on the lines corresponds to the pressure tap locations shown in Figure 13. The temperature data for the first tube are shown in Figure 18. The temperature data for the second and third tubes are presented in Figure 19 as the 0 to 2400 sec segment of data. All the numbering on the lines corresponds to the thermocouple locations depicted in Figure 13 except for T-0 which is located on the skin of the first tube in this test. The data show that film boiling is predominating in the first tube as evidenced by the high temperatures measured internally at the exit of the first tube and slug flow is occurring as evidenced by the variations in the temperature measurement at the exit to the first tube.

Section 2: The methane flow rate was initially adjusted to 3.6 kg/hr (8.0 lb/hr) for about 2 min, then readjusted to 4.5 kg/hr (10 lb/hr) and maintained at that level for 40 min. During that period, a slow pressure decay was noted to develop at P_1 and downstream, indicating a buildup of deposits in Tube 1. This trend continued throughout the period. The methane flow was stopped at that time and the system was leak checked but no leaks were apparent. The fouling in Tube 1 was removed by passing helium through the system.

The pressure data for this section of the test are shown in Figure 17 as the 2800 to 5600 sec segment of data. The corresponding temperature data for the first tube are shown in Figure 18. The temperature data for the second and third tubes are shown in Figure 19. The film boiling and slug flow are evidenced by the temperatures measured at the outlet to the first tube. For a brief segment of the test, 4200 to 4700 sec, it appears that nucleate boiling is occurring as evidenced by the drop in temperatures on the skin of the first tube, T-2 and T-0 values. With the gradual increase in ΔP across the first tube, the desired temperature levels were not maintained during the test.

Section 3: Methane flow rate was adjusted to 2.5 kg/hr (5.5 lb/hr) and maintained for 45 min. After the initial 37 min, a momentary high ΔP was observed between P_1 and P_2 , indicating a temporary clogging of the

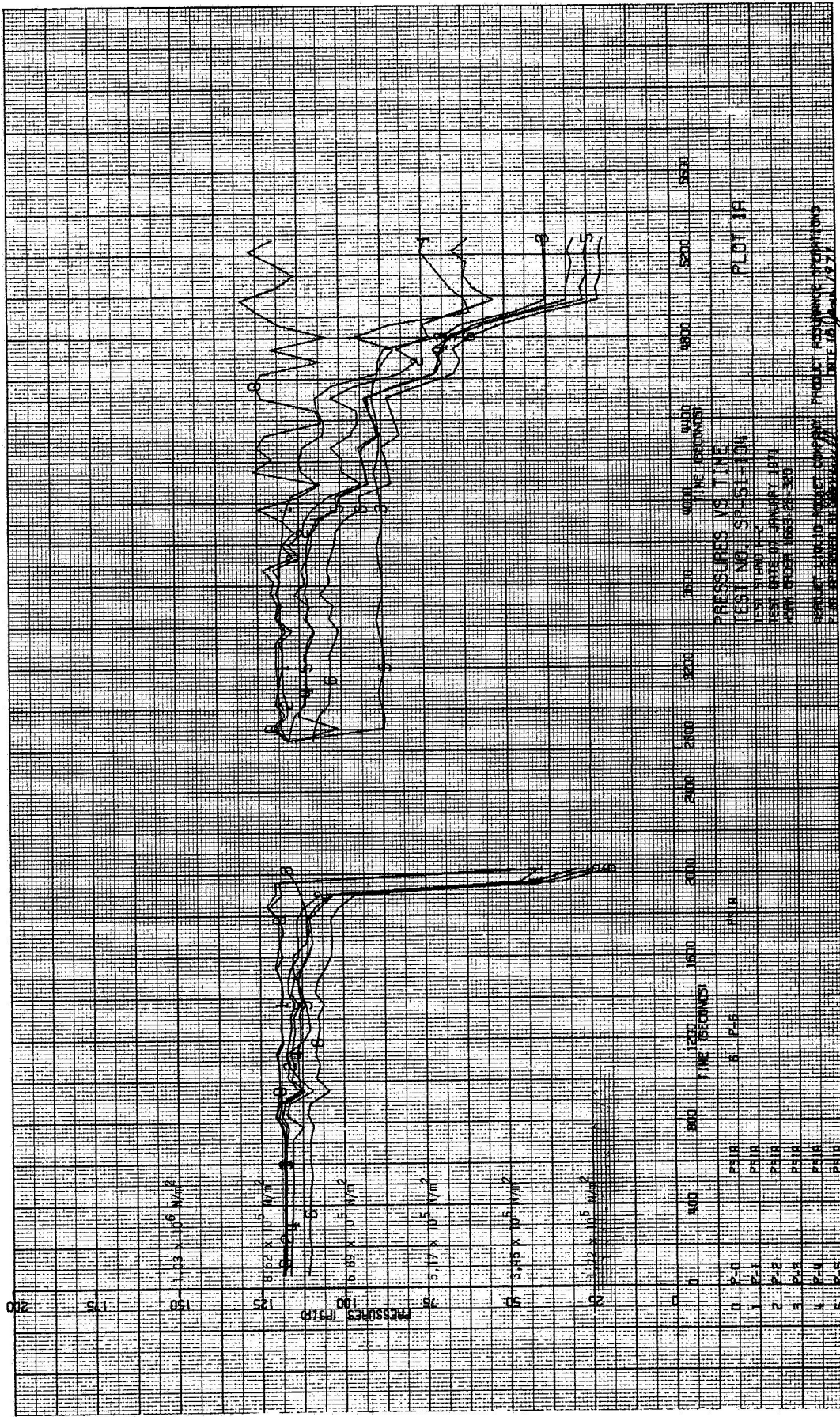


Figure 17. - Pressure Data for Test 2, Sections 1 and 2

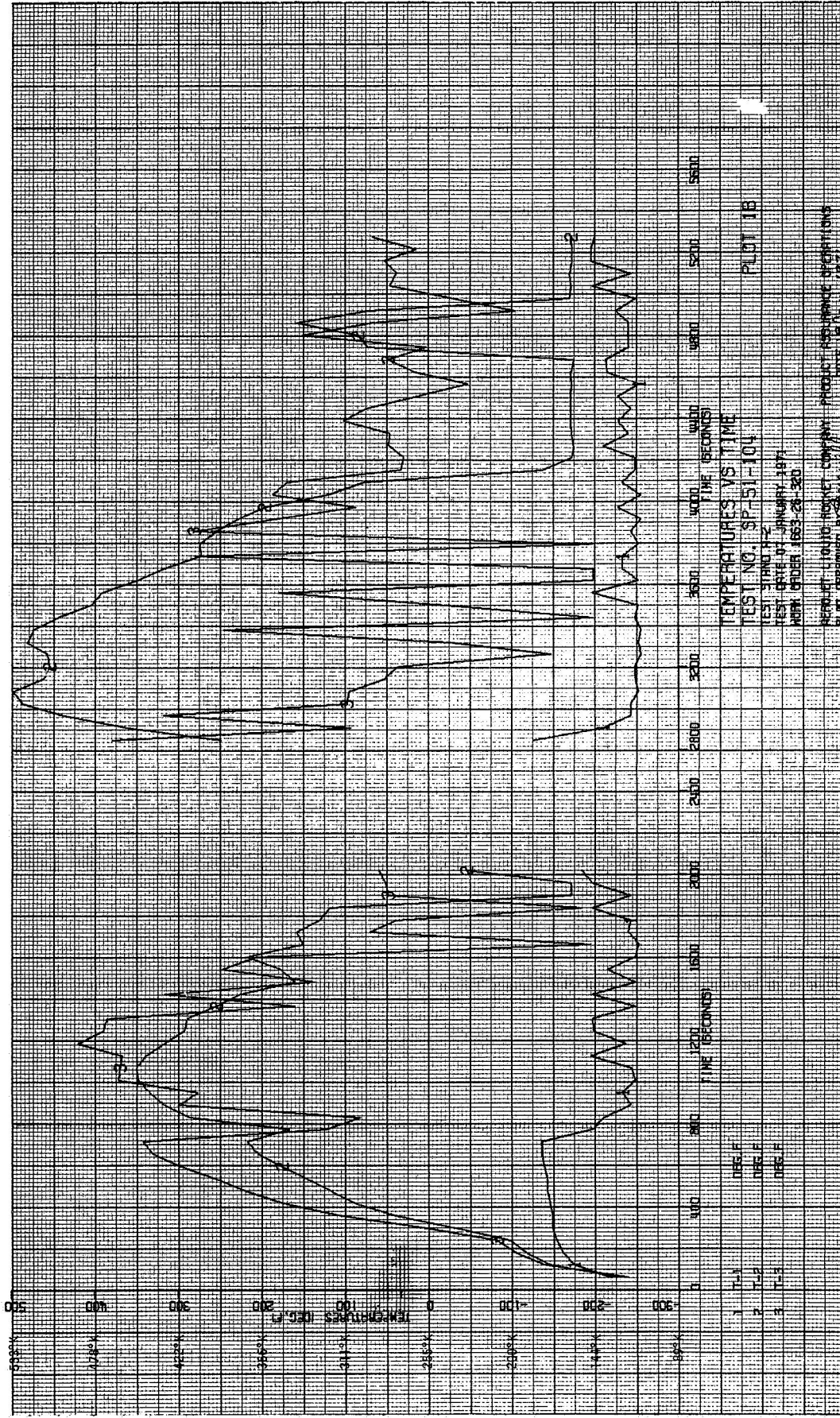


Figure 18. - Temperature Data for Test 2, Sections 1 and 2

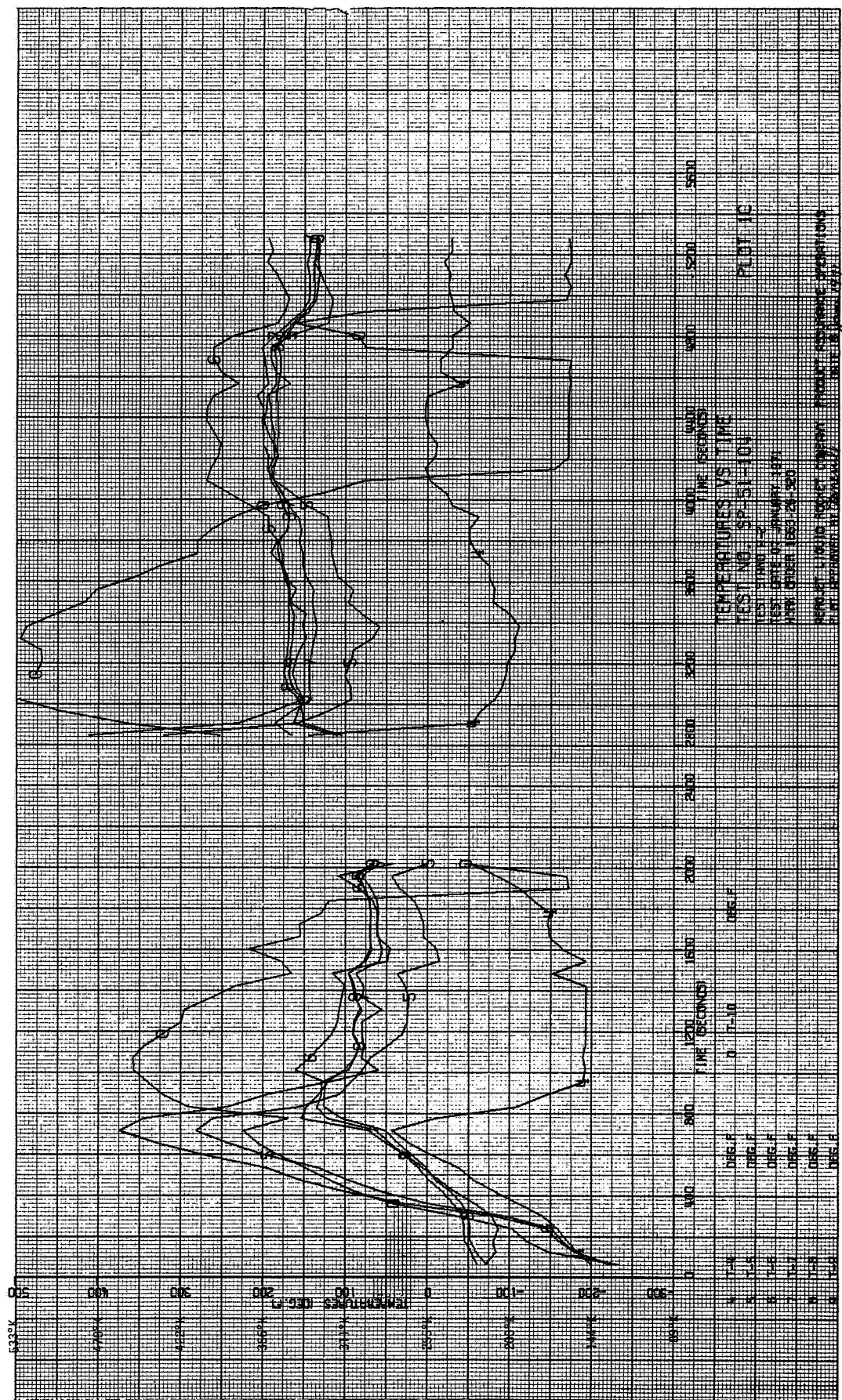


Figure 19. - Temperature Data for Test 2, Sections 1 and 2

screen in Header 1. After 45 min of operation, a high ΔP developed between P_0 and P_1 , indicating Tube 1 was fouled, and the methane flow was stopped. The plug in the system was removed with helium.

The pressure data for this section of the test are presented in Figure 20 as the 6000 to 8800 sec segment of data. The pressure tap at location 3 was clogged with ice and the pressure value does not relate to the pressure in the second header. The corresponding temperature data for the first tube are presented in Figure 21 and the temperature data for the second and third tubes are presented in Figure 22. The first tube operated primarily in the film boiling regime and the slug flow was apparent. The temperature levels in the second and third headers were higher than the desired values. In addition, the gas temperature in the second header was dropping approximately 50°F (28°K). This indicated that the headers required external heating in addition to the insulation.

Section 4: Methane flow rate was adjusted to 2.5 kg/hr (5.5 lb/hr) and flowed for about 12 min without incident until the test was terminated. The pressure data are presented in Figure 20 as the 9700 to 10,700 segment. The corresponding temperature data are shown in Figures 21 and 22. The film boiling regime was evident in the first tube as in the previous sections of the test.

The clogging of the 0.32 cm (1/8 in.) tubing leading to the P_3 transducer had been observed in Tests 1 and 2. Therefore, in an effort to avoid the recurrence of plugging of the transducer lines, the pressure taps on all the headers were relocated so that: (1) the pressure tap was not directly in line with the inlet and outlet flow ports, and (2) the transducer lines had no low points in which liquid (water) could accumulate and freeze to form a plug.

In addition to this change, thermocouples were installed in the header sections employing the pressure tap locations opposing the fluid flow ports. The new shielded thermocouple junctions are located on the axis of and about 0.16 cm (1/16 in.) from the fluid flow ports.

The significant items to be noted from Test 2 are that the clogging mechanism is predominant in the first tube section in which the methane is vaporized and that the heat exchanger does not operate in a stable manner at the 4.5 kg/hr (10 lb/hr) flow rate.

c. Heat Exchanger Test 3

The purpose of the third test was to determine the effect of gelant concentration on the potential clogging mechanisms. The gelled methane fuel used in this test contained 1.1 percent water as gelant and 20-mesh filter screens were present in each of the headers. Test 3 can be divided into two sections of slightly different duration, but of similar operating parameters.

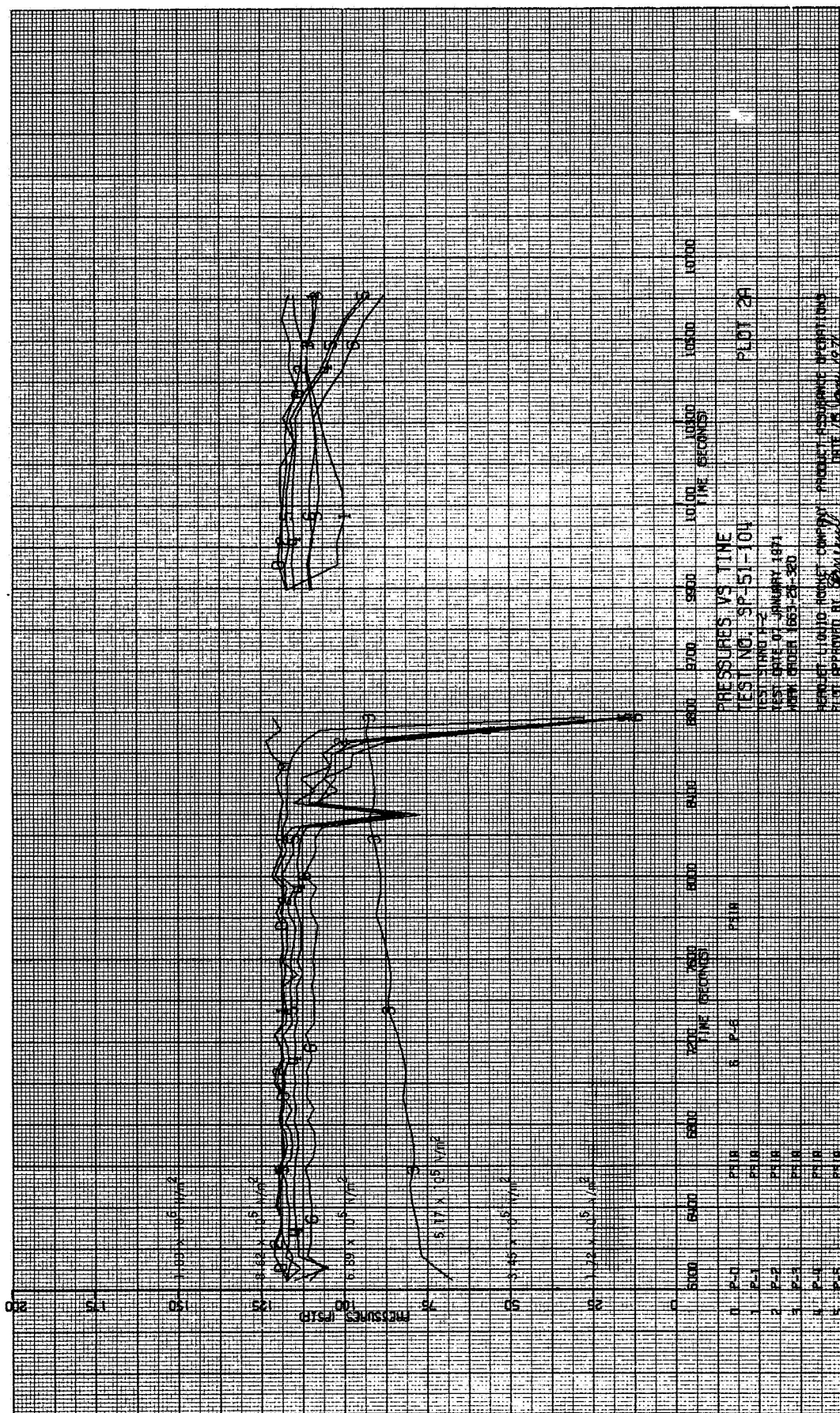


Figure 20. - Pressure Data for Test 2, Sections 3 and 4

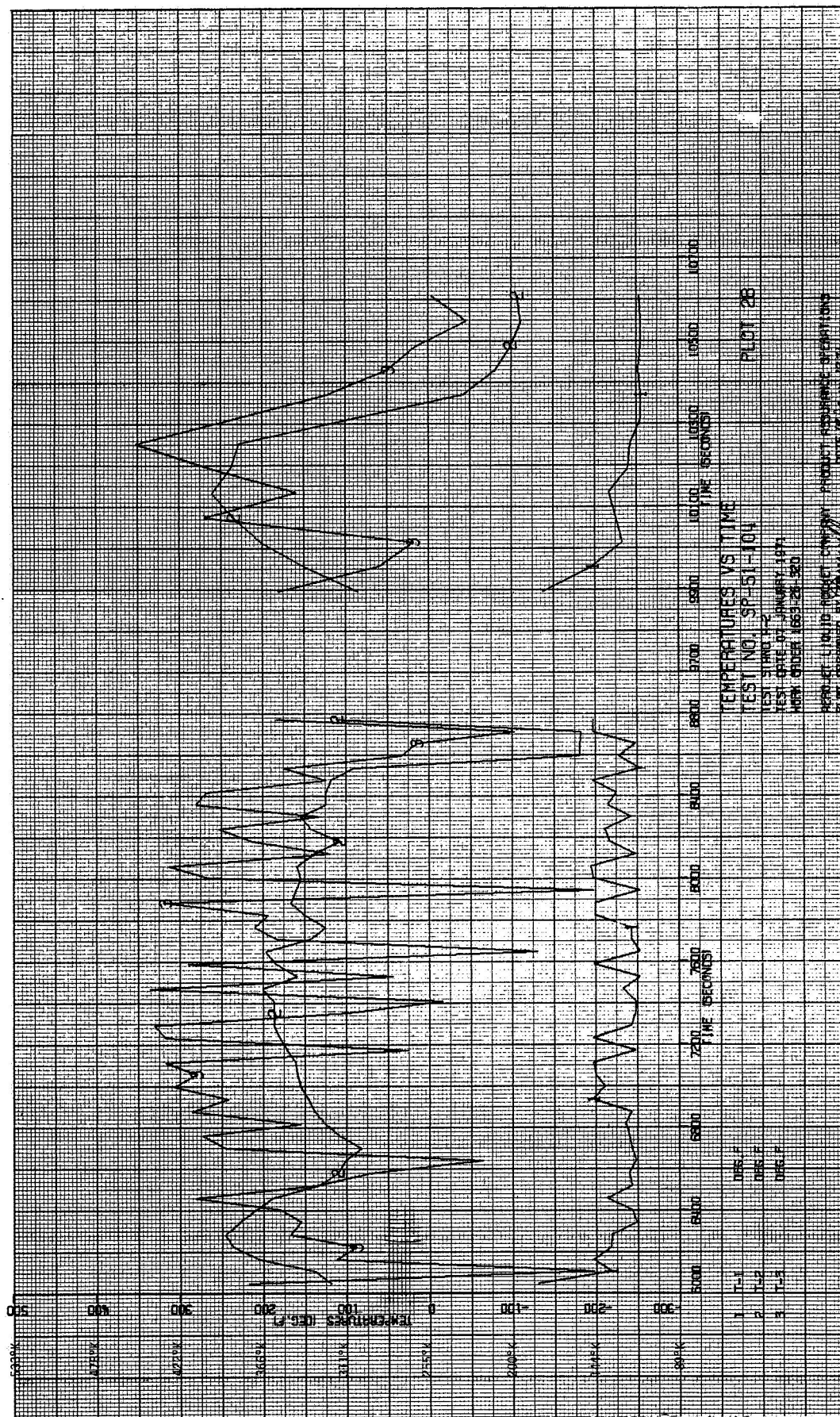


Figure 21. - Temperature Data for Test 2, Sections 3 and 4

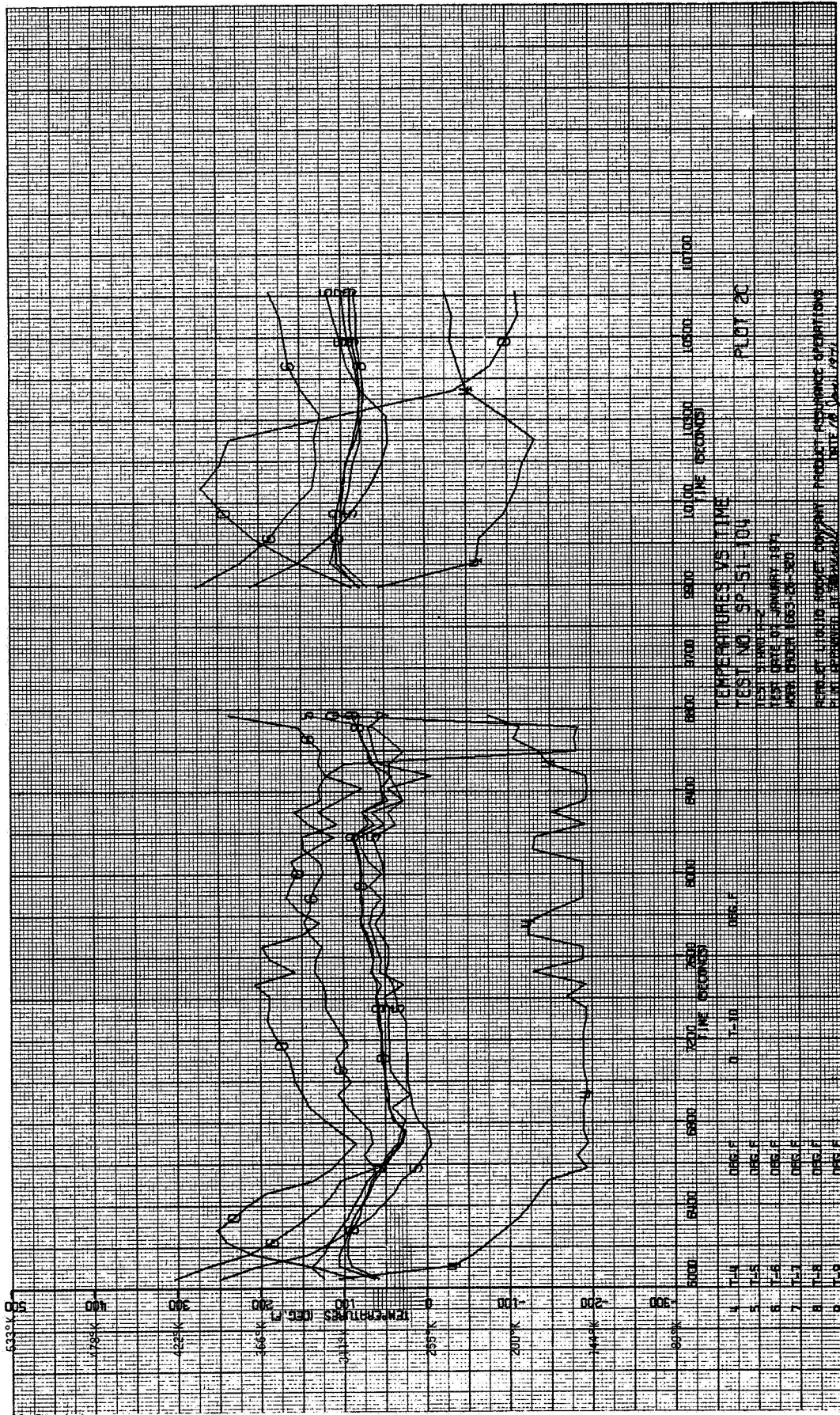


Figure 22. - Temperature Data for Test 2, Sections 3 and 4

Section 1: Gelled methane flow was initiated and maintained at 2.6 kg/hr (5.8 lb/hr) for 8 min. The flow was then increased to 4.2 kg/hr (9.5 lb/hr) for an additional 32 min. A ΔP initially appeared at P₄-P₅ (Tube 3) after about 4 min at the higher flow rate. After another minute, a ΔP appeared at P₃-P₄ (Header 2); after another 6 min, a $2.4 \times 10^5 \text{ N/m}^2$ (35 psi), but temporary ΔP occurred at P₁-P₂ (Header 1). After another 5 min a severe and persistent ΔP occurred at P₁-P₂ (Header 1). Finally, after another 5 min an increasing ΔP occurred at P₀-P₁ (Tube 1). Methane flow was stopped and the tubes and headers freed of blockage by passing helium through the system.

The pressure data are presented in Figure 23 as the 0 to 3200 sec segment. Although the data points are plotted for every 60 sec and some of the transients are not presented in the plot, the general trends are very apparent. The temperature data for the first tube are presented in Figure 24. The temperature data for the second and third tubes are presented in Figure 25. The T-10 value was measured at the exit of the third tube as shown in Figure 13. The film boiling regime is again occurring in the first tube during the major portion of the test. The temperature oscillations at the exit of the second tube (T-6) indicate that some liquid droplets are being transported through the second tube. The heating of the second header has eliminated the drop in temperature of the gas as it passes through the header.

Section 2: Gelled methane flow was established for 6 min at 2.6 kg/hr (5.8 lb/hr), then increased to 4.2 kg/hr (9.5 lb/hr) and maintained at that level for an additional 16 min. A large ΔP , $3.4 \times 10^5 \text{ N/m}^2$ (50 psi), appeared at P₄-P₅ (Tube 3) and a slight ΔP , $3.4 \times 10^4 \text{ N/m}^2$ (5 psi), appeared at P₂-P₃ (Tube 2) after about 5 min at the higher flow rate. The system then operated relatively stably for another 15 min until an increasing ΔP at P₁-P₂ (Header 1) occurred, when the methane flow was stopped.

The pressure data for this section of the test are presented in Figure 23 as the 4200 to 5800 sec segment. The corresponding temperature data are presented in Figures 24 and 25. Although the pressure drops were increasing in the system, the desired temperature levels were maintained in the apparatus.

It appeared that much of the difficulty of maintaining methane flow for extended periods resulted from blockage in the heat transfer tubes as well as the fouling of filter screens. The data also suggest that a definite sequence of events ultimately results in the flow restriction. The sequence is: (1) Tube 3 becomes constricted, (2) Tube 2 becomes constricted, (3) Header 1 and/or Tube 1 become constricted. This sequence suggests that the cause of difficulty is the partial melting, condensation and refreezing of the small ice particles at the entrance to Tube 3. This results in a small, momentary drop in flow rate which allows the condensation of liquid or accumulation of ice particles in Tube 2. Finally, ice particles accumulate in the Header 1 screen or in Tube 1 and a high ΔP develops which necessitates stopping the methane flow.

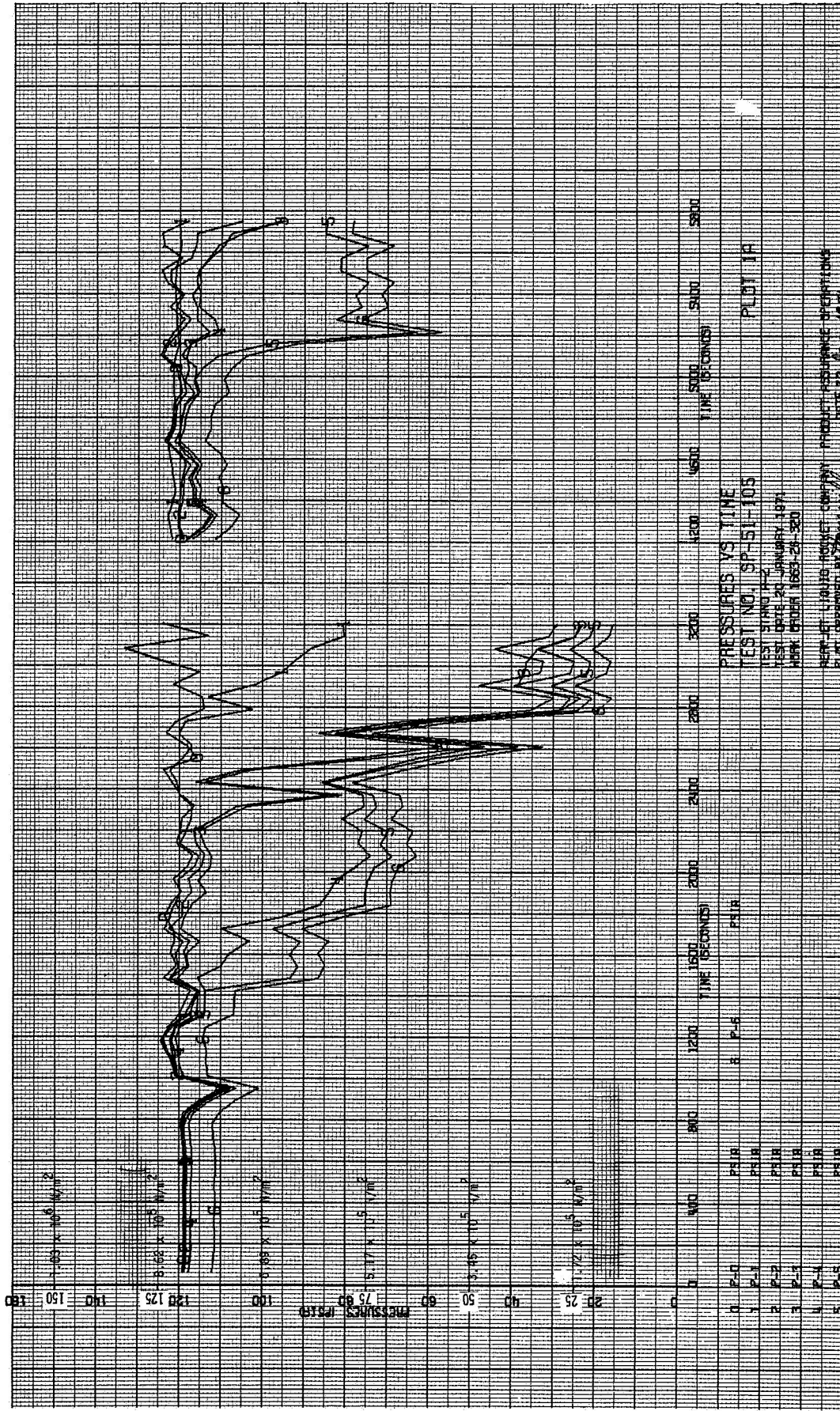
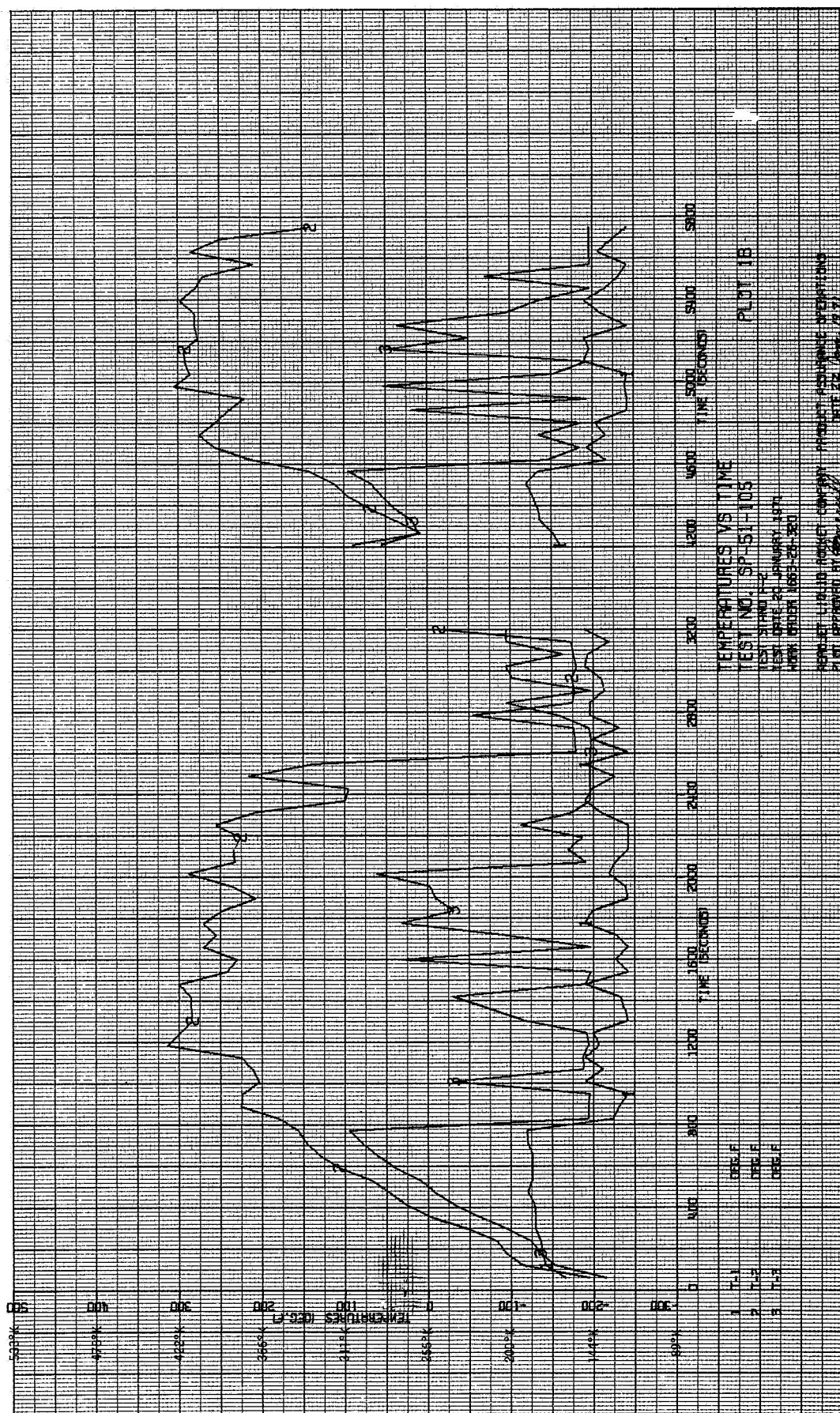


Figure 23. - Pressure Data for Test 3



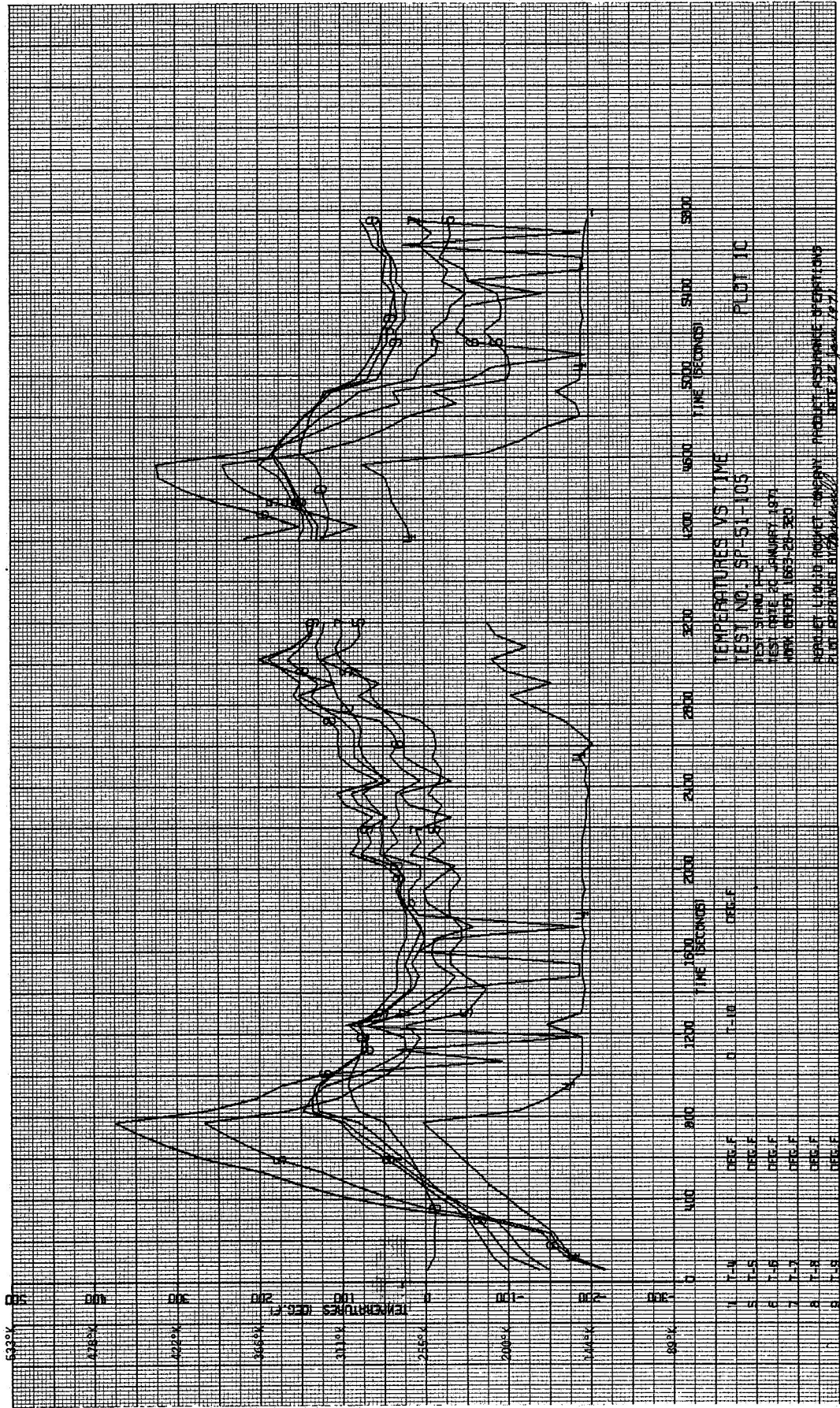


Figure 25. - Temperature Data for Test 3

It was concluded from this test that, at the higher flow rate and under the power input conditions of the test, deposition of ice particles and/or fouling of screens occurs after 30 min of operation. The gelant concentration appeared to have only a secondary effect on the clogging mechanism.

d. Heat Exchanger Test 4

The purpose of this test was to determine whether the 4.5 kg/hr (10 lb/hr) flow rate of gelled methane could be maintained if the screens were removed. This test was performed using gelled methane containing 1.1% water as gelant.

Considerable difficulty was encountered in the start-up of this experiment. The venturi tube became clogged twice by large particles of solid material, believed to be formed in the gel preparation-gel holding tank line and swept into the holding tank when additional gel was prepared prior to this test. The venturi was removed to eliminate this problem. Attempts to flow gel at a high flow rate, 4.5 kg/hr (10 lb/hr), also resulted in clogging the system, probably because of large particles of ice in the system.

After this initial difficulty, however, the flow of gelled methane was established at about 2.6 kg/hr (5.8 lb/hr). This flow rate was maintained for a period of 133 min. During this period of time, no significant ΔP was observed in any of the component hardware. On a few occasions small transient ΔP 's were noted; these were believed to be the result of passage of comparatively large particles of ice through the system.

The data derived in this test showed that a transition in heat transfer mechanism occurred after about 65 min of operation. The first portion of the test was characterized by a wide variability in T_3 indicating slug flow characteristic of film boiling. Tube 1 wall temperatures were high, 339 to 353°K (+150 to 175°F). Also, T_6 variability indicated occasional cold fluid reaching the exit of Tube 2. However, at about 70 min, the Tube 1 wall temperature dropped to near 150°K (-190°F) and T_3 became very steady at 147°K (-195°F). The previously fluctuating T_6 also became substantially more stable in the temperature range 283 to 311°K (50 to 100°F).

After more than an hour of stable nucleate boiling in Tube 1 at the 2.6 kg/hr (5.8 lb/hr) flow rate, the flow rate and power input to the system were increased gradually until a flow rate of 4.5 kg/hr (10 lb/hr) was achieved. The system operated smoothly for about 10 min at the higher flow rate when a high ΔP developed at P_0 - P_1 (Tube 1) indicating blockage of Tube 1, perhaps as the result of an ice particle hanging up or the development of a deposit of gelant material.

The pressure and temperature data obtained during the test are given in Figures 26, 27 and 28. In Figure 26, the pressure data for the test are presented. The oscillation of the line designated as 3 is due to



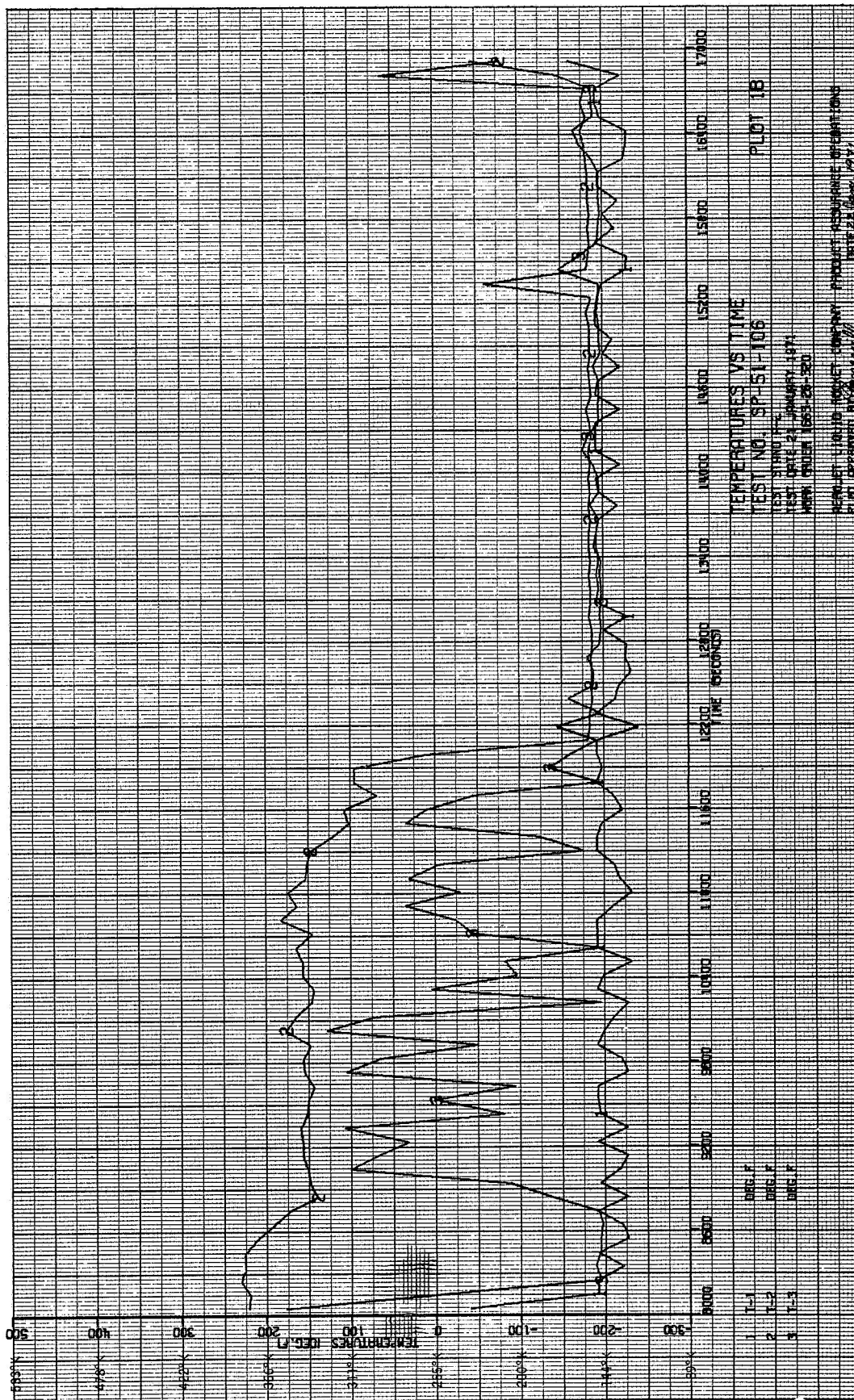


Figure 27. - Temperature Data for Tube 1 During Test 4

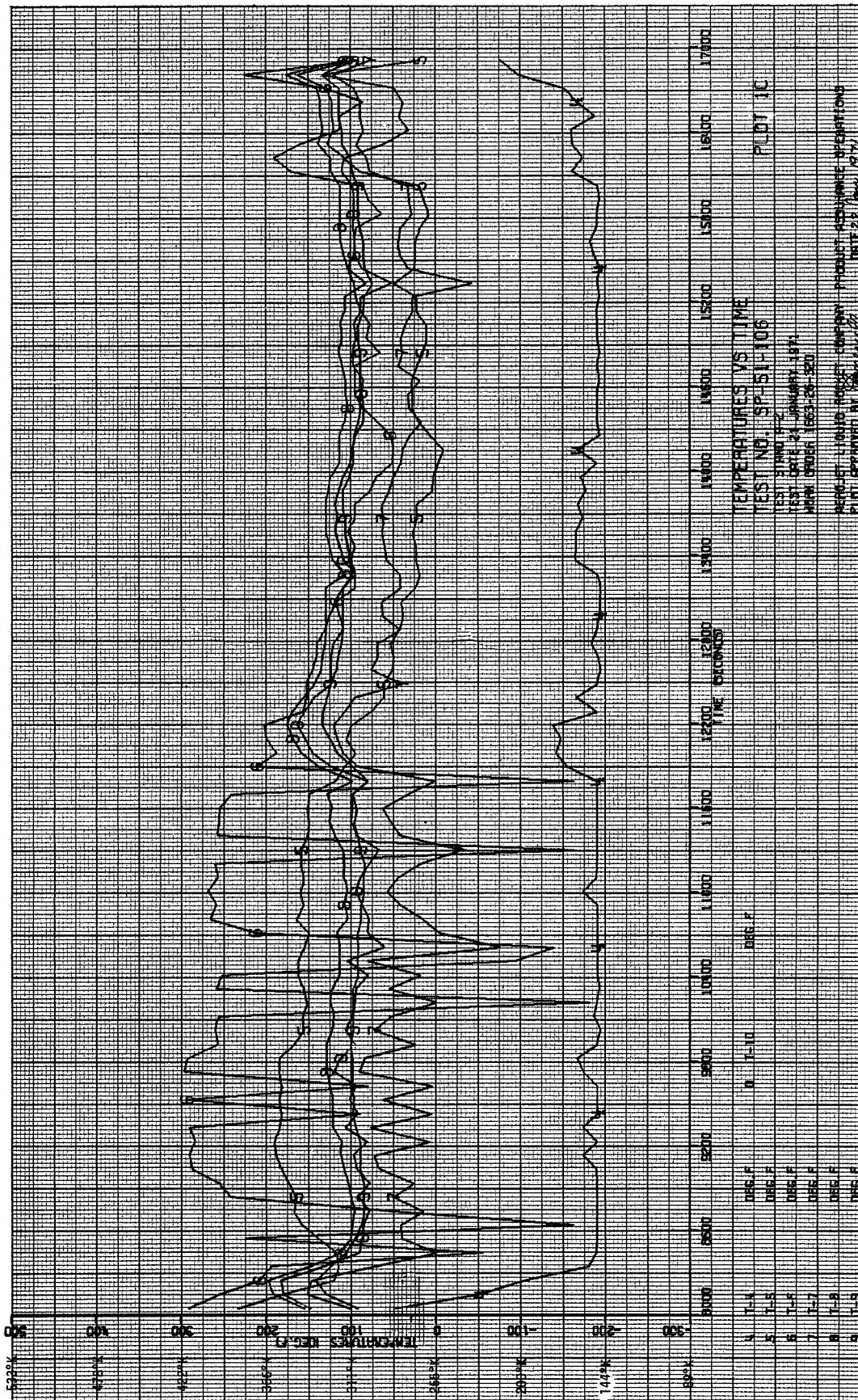


Figure 28. - Temperature Data for Tubes 2 and 3 During Test 4

partially clogging of the line to the transducer. Similarly, the drop in the value of the line designated as 4 was caused by clogging of the line to the transducer. The lines to the transducers were at the same temperature as the box, about 116°K (-250°F), and it is not unexpected that droplets of water would freeze in these lines. The locations of the pressure taps are shown in the schematic diagram in Figure 13.

In Figure 27, the temperature data are plotted for Tube 1. The numbering of the lines corresponds to the thermocouple locations as shown in Figure 13. Line 1 represents the temperature of the liquid 5 cm (2 in.) from the inlet of the tube; Line 2 is the external surface temperature of the tube at its midpoint; and Line 3 is the temperature at the outlet of the tube. The transition from film to nucleate boiling is shown by the dramatic drop in the values represented by Line 2.

In Figure 28, the temperature data for Tubes 2 and 3 are presented. The numbers on the lines correspond to the thermocouple locations shown in Figure 13. The significant item to be noted from the data is that relatively stable operation resulted after the nucleate boiling regime was established in Tube 1.

The transition of the heat transfer mechanism from film to nucleate boiling (which occurred spontaneously in this test) suggested that the nucleate boiling regime is only slightly favored in this system. Therefore, it was hypothesized that the installation of a turbulence inducer in Tube 1 would establish the nucleate boiling regime immediately and would allow stable operation at a higher flow rate of about 4.5 kg/hr (10 lb/hr). The flow rate of 4.5 kg/hr (10 lb/hr) in the current apparatus was not possible for the duration goal of two hours.

e. Heat Exchanger Test 5

The purpose of this test was to establish that a turbulence inducer installed in the first tube would cause the stable operation of the heat exchanger. This test was performed using gelled methane containing 1.0 percent water as gelant. No filter screens were installed in the headers. The turbulence inducer consisted of a stainless-steel strip 0.110 in. by 0.010 in. with one 360° twist/7.6 cm (3 in.). It was installed in Tube 1 prior to the test. This installation also reduced the internal cross-sectional area of tube by 5.7 percent.

Gelled methane was flowed at a rate of 2.5 kg/hr (5.5 lb/hr) for four minutes, then increased to 3.5 kg/hr (7.8 lb/hr) for five minutes, and finally increased again to 4.2 kg/hr (9.2 lb/hr) and maintained at that level for 111 min.

Throughout the period of methane flow no significant pressure drops were observed to develop in the system. P₃ and P₄ transducer lines were observed to clog (in that order) as indicated by their responses.

The methane flow rate was remarkably steady throughout the test. Occasional ΔP and flow rate fluctuations were observed; these fluctuations appeared to originate in Tube 2 or Header 2 and are believed to be the result of occasional, agglomerated ice particles hanging up in or near the exit of Tube 2. These disturbances were of very small magnitude and are considered to be insignificant.

The heat transfer mechanism in Tube 1 was nucleate boiling throughout the test and the installation of the turbulence inducer in Tube 1 proved to be very effective in inducing nucleate boiling, which led to stable operation.

The pertinent pressure and temperature data for Test 5 are presented in Figures 29 and 30. The pressure data are shown in Figure 29 and the numbering of the lines corresponds to that shown in Figure 13. The temperature data are presented in Figure 30 and the numbering of the lines corresponds to that shown in Figure 13. The significant item to be noted from the data is that the operation of the heat exchanger was very stable as compared to the operation of the heat exchanger in Test 4.

4. Discussion of the Results

The heat exchanger was installed and operated under very unfavorable conditions. The basis for this approach was to verify that the gelled fuel could be flowed under these conditions and, having accomplished this, that the flow of the gelled fuel could then be assured under more favorable conditions.

Two characteristics of the system are particularly notable in this regard: (1) the presence of the headers, and (2) the vertical orientation of the heat exchanger tubes. The presence of the headers causes a very rapid decrease in the velocity of the fluid as it exhausts from the tubes; this decrease in velocity tends to allow the accumulation of the condensed particles in the lower portion of the headers. The orientation of the heat exchanger is such that, with the exception of Tube 1, the flow of fluid is upward and requires that the condensed phase be moved against the force of gravity. These factors are very unfavorable to the smooth continuous flow of fluid in the heat exchanger.

The test data indicate that the deposition of gelant on the screens in the headers does not represent a limiting factor in the flow of the gelled methane. On the contrary, clogging of the heat exchanger tubes appears to be the chief cause of difficulty in achieving continuous flow at comparatively high flow rates.

The use of a turbulence inducer in the first tube permits the stable operation of the heat exchanger at the higher methane flow rate and induces nucleate boiling of the liquid. Under these conditions of heat transfer, no fouling of the tubes was observed.

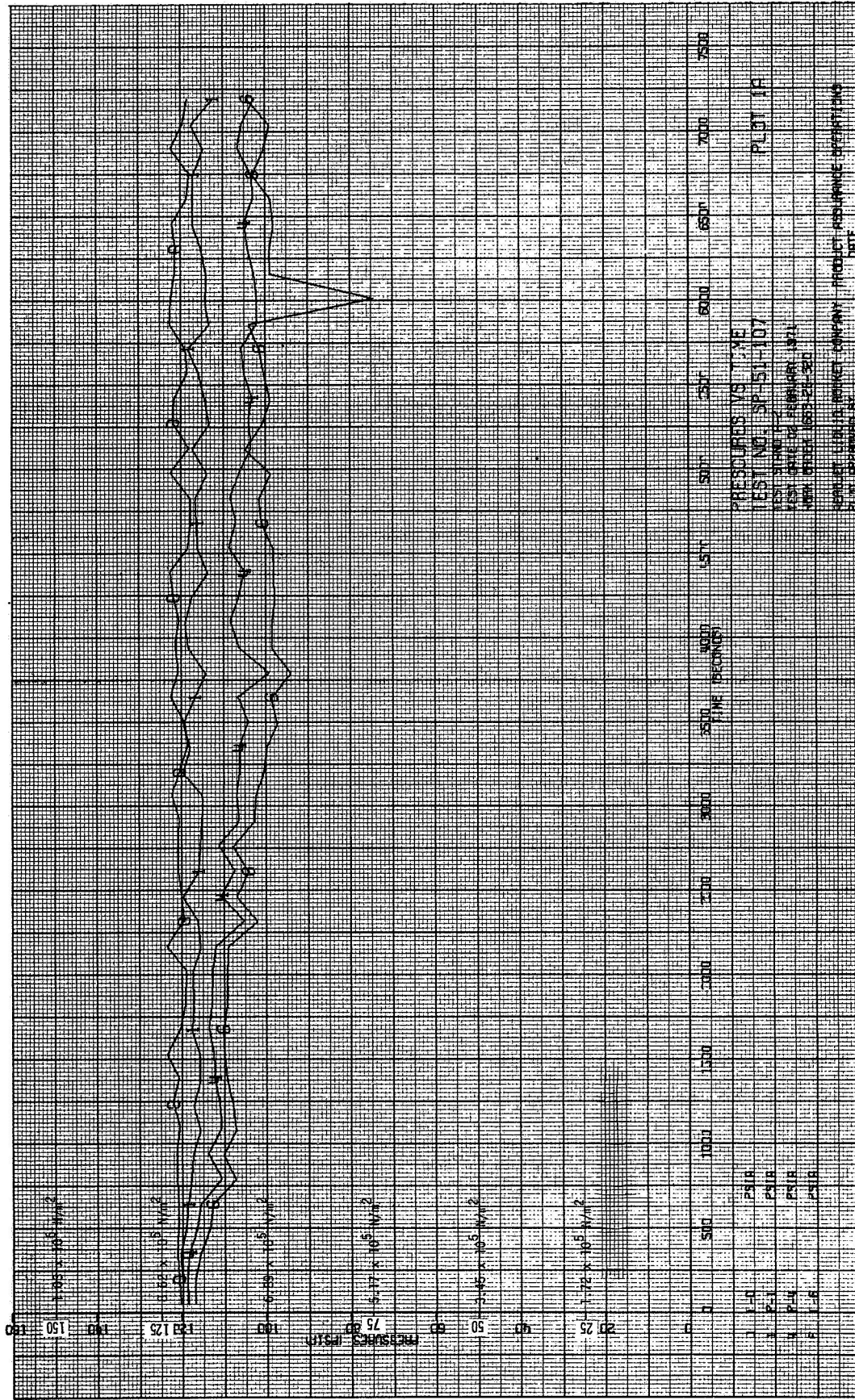


Figure 29. - Pressure Data for Test 5

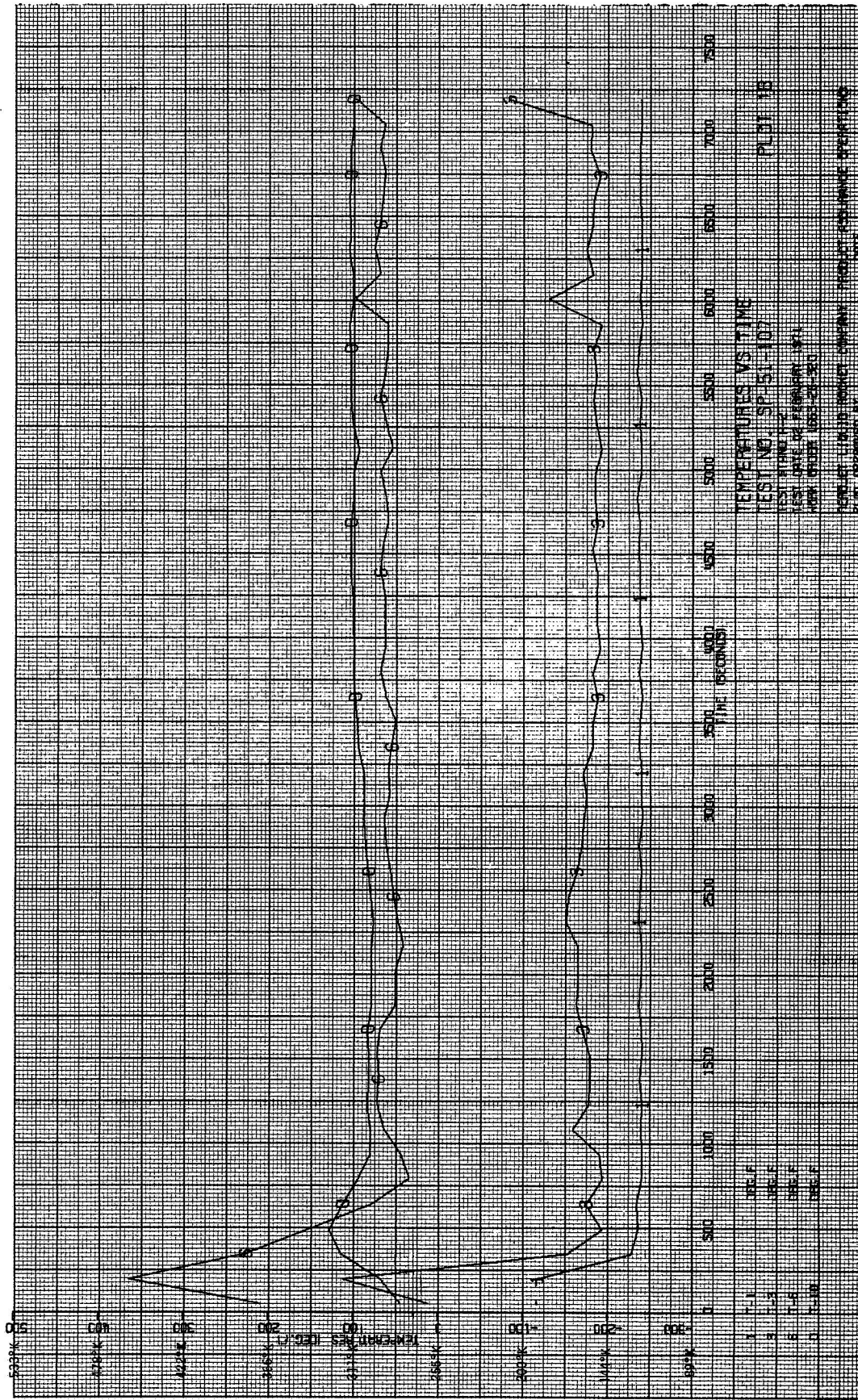


Figure 30. - Temperature Data for Test 5

Long-term, continuous operation of the system at low flow rates can be achieved with either nucleate or film boiling when screens are absent. When screens are included in the system, fouling in the tubes appears to occur somewhat sooner.

On the basis of these test data, it is concluded that the inclusion of a turbulence inducer to induce nucleate boiling will permit the long-term, stable operation of the heat exchanger, at both high and low flow rates, even with filter screens installed.

III. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are drawn from this investigation.

1. Gelation of liquid methane with either water or methanol particles provides a satisfactory method to reduce the rate of nitrogen absorption in subcooled liquid methane to an insignificant value.
2. The increased specific fuel consumption will not be excessive due to the gelant required. Less than 1.5 weight percent water or methanol is sufficient to reduce the nitrogen absorption rate to an insignificant value.
3. Gelled liquid methane is storable for periods exceeding 100 hr near the normal boiling point of liquid methane. No significant gel structure degradation occurs during this time span.
4. The gels can be transferred through properly designed heat exchangers at comparatively high flow rates (4.5 kg/hr-10 lb/hr) without clogging by proper selection of the operating conditions. The formation of methane hydrates does not appear to be a problem in the heat exchanger.
5. The handling qualities of the gelled fuel are not impaired by fuel vaporization until the boiloff levels approach 90 percent. By proper design of the apparatus, the material is transferable.

B. RECOMMENDATIONS

1. Liquid methane gelled with methanol should be investigated in a series of heat exchanger tests in order to evaluate the merits of the product.
2. The preparation of gelled methane slush and its characteristics should be investigated.
3. The economics of the gelation procedure should be investigated.
4. Additional heat exchanger tests should be conducted with methane gelled with water to determine the heat transfer coefficients of the material.

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